Breakdown Properties of Atmospheric Air with Switching Overvoltages

by

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Certificate

This is to certify that the work contained in the thesis entitled Breakdown Properties of Atmospheric Air with Switching Overvoltages by Surendra Singh has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

July 1998

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Abstract

Dielectrics, the indispensible part of modern power systems are subjected to severe stress of lightning and switching impulsess. The dielectric used should be able to withstand the severest of the impulses. In this work four sphere-sphere configurations of radius 20 mm. 15 mm, 12.5 mm, 7.5 mm are used. The gap distance is varied from 2 cm to 15 cm making the field to vary from weakly non uniform to non uniform field. This study analyses the variation of breakdown strength and breakdown voltage under different switching impulses. It is also studied how breakdown strength of dielectric changes under different field configurations.

How the polarity effect under different field configurations affects the breakdown strength is also studied. The propagation time and propagation velocity (in cm/μs) of streamer in the dielectrics are also measured. Their changes under different field configurations are also recorded.

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Chapter 1

INTRODUCTION

Electric power transmission and distribution systems are frequently subjected to two kinds of transient over voltages. The magnitude of these voltages may greatly exceed the peak value of the normal operating voltage.

The first kind of transient overvoltage is lightning impulse,which are originated by lightning strokes hitting overhead lines or the busbars of a outdoor stations. The amplitude of lightning overvoltages is very high. The magnitude of static over voltage acquired by the clouds is insignificant for the li strikes,however the magnitude of transient current injected into the system is of importance. Lightning currents upto an order of 100 kA or more are known. Each stroke is followed by a travelling wave,whose steepness may exceed 100kA/microsec. Overvoltages developed on the lines depends upon their surge impedance. This may get chopped across devices like horn gaps,lightning arresters etc according to their settings. The residual voltage stresses the insulation of power transformer

and other high voltage equipment severely.

The second kind of over voltages is switching impulses. The amplitude of these impulse voltages is always related to the operating voltage,impedance of the system and switching conditions. These high voltages are sufficient enough to stress the dielectric severely. The damage,if caused, to the dielectric is permanent and irreparable. As dielectric is an indispensible part of modern electric equipments,it becomes important to study the behaviour of dielectric under these transient overvoltages. Objective of this work is to study how the shape ,polarity of the impulse wave as well as the field conditions affect the breakdown strength of the atmospheric air. The propagation time of breakdown channel is also measured for diffrent shape of switching impulses under diffrent switching conditions.

Chapter 2

GENERATION AND MEASUREMENT OF IMPULSE VOLTAGES

The generation and measurement of high voltage impulses is a subject in itself and involves sophisticate equipments and techniques. Impulse generator is a common source of generation of high voltage lightning and switching impulses Theory, design and operation of impulse generator will be discussed here. Although there are several techniques for measurement of impulse voltages but the technique of voltage devider,which is used in the experimental setup also , will also be discussed.

2.1 Standard Defined for Impulse Voltages

Though the actual shape of switching impulses vary strongly with operating voltage,impedan of the system and switching conditions,yet it becomes necessary to simulate these tran-

sient voltages by simple means for testing purposes. Various national and international standards have been set to define impulse voltages. An impulse voltage is defined as a unidirectional voltage which rises rapidly to peak value and then decays relatively slowly to zero. The distinction between lightning and switching impulses is made depending upon their rate of rise and decay. Impulse voltages with a front duration varying from less than one upto a few tens of microseconds are considered as lightning impulses. A typical lightning impulse is shown in figure 2.1 . Time T_1 is the rise time and T_2 is the tail time. It is standard to define impulses voltages by their T_1/T_2 ratio. For a typical lightning impulse value of T_1/T_2 is 1.2/50 microseconds. The specification permits a tolerance of upto $\pm 30\%$ of T_1 and $\pm 20\%$ for T_2. Lightning impulses are of short duration.

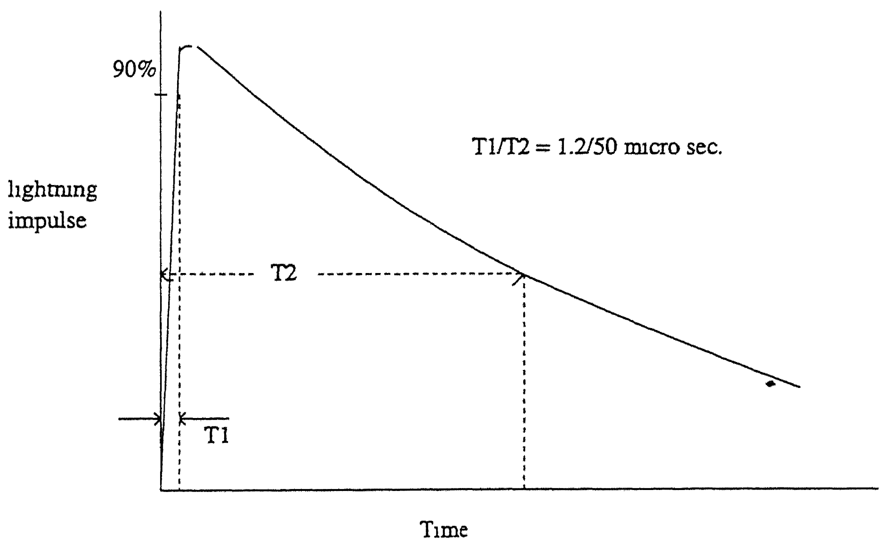


Figure 2.1: A typical Lightning Impulse

typical value of T_1/T_2 *for a switching impulse is* $(250 \pm 20\%)/(2500 \pm 60\%)$. A typical switching impulse is shown in figure 2.2. As in this case it is not easy to locate

90% point due to flateness of the peak,the value of T_1 corresponds to the peak of the impulse.

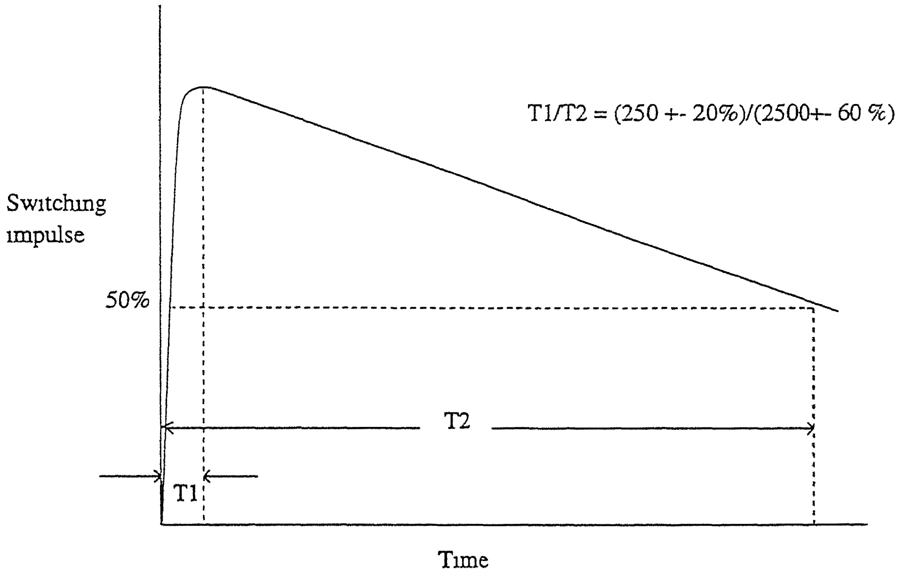


Figure 2.2: A Typical Switching Impulse

2.2 Theory of Impulse Generator

The rapid rise and slow decay of impulse voltages can be generated with two energy storages.as wave shape is composed of the superposition of two exponentialfunctions. The load of impulse generator are generally capacitive as insulation systems are tested. This load therefore contribute to the stored energy. The second source of energy is provided by an additional capacitor.

2.2.1 Single Stage Generator Circuits

Two basic circuits for single stage impulse generators are shown in figure 2.3. the capacitor C_1 is charged from a dc source until the spark gap G breaks down. This spark

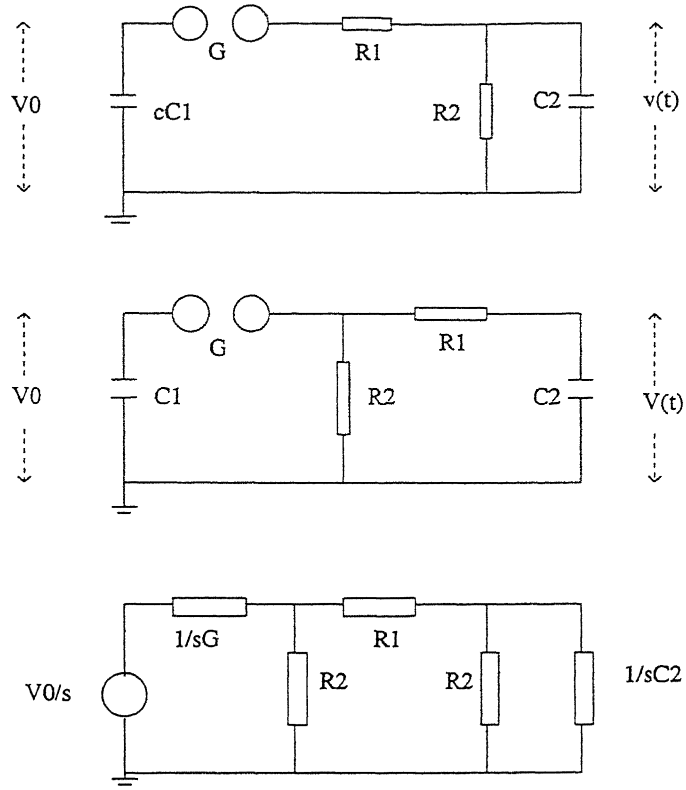


Figure 2.3: (a) Single stage impulse generator circuit (b) More efficient impulse generator circuit (c) Laplace transform circuit

gap acts as a voltage limiting and voltage sensitive switch. Its ignition time (time to break down) is very short compared to rise time T_1.

The resisters R_1,R_2 and the capacitor C_2 form the waveshaping network. R_1 primarily damps the circuit and controls the front time T_1. R_2 will discharg the capacitors and therefore controls the wave tail. The capacitor C_2 represents the full load i.e. the object under test.

The maximum energy stored in the discharge capacitor C_1 is

$$W = \frac{1}{2}C_1({V_{0max}}^2) \tag{2.1}$$

The value of C_1 is very large compared to C_2. The C_1 determines mainly the cost of the

generator.

Using Laplace Transform we get,

$$V(s) = \frac{V_0}{s} \cdot \frac{Z_2}{Z_2 + Z_1} \tag{2.2}$$

where

$$Z_1 = \frac{1}{C_1 s + R_1} \tag{2.3}$$

$$Z_2 = \frac{R_2/C_2 s}{R_2 + \frac{1}{C_2 s}} \tag{2.4}$$

By substitution we get

$$V(s) = \frac{V_0}{k} \frac{1}{(s^2 + as + b)} \tag{2.5}$$

where,

$$a = \left(\frac{1}{R_1 C_1} + \frac{1}{R_1 C_2} + \frac{1}{R_2 C_2}\right) \; ; \tag{2.6}$$

$$b = \frac{1}{R_1 R_2 C_1 C_2} \; ; \tag{2.7}$$

$$k = R_1 C_2 \tag{2.8}$$

For the circuit in figure 2.3 (b) the constants are

$$a = \left(\frac{1}{R_1 C_1} + \frac{1}{R_1 C_2} + \frac{1}{R_2 C_1}\right) ; \tag{2.9}$$

$$b = \frac{1}{R_1 R_2 C_1 C_2}; \tag{2.10}$$

$$k = R_1 C_2 \tag{2.11}$$

Hence,

$$V(t) = \frac{V_0}{k(\alpha_2 - \alpha_1)} [\exp(-\alpha_1 t) - \exp(-\alpha_2 t)] \tag{2.12}$$

where α_1 and α_2 are the roots of the equation $s^2 + as + b = 0$

$$\alpha_1, \alpha_2 = -\frac{a}{2} \pm \sqrt{\left(\frac{a}{2}\right)^2 - b} \tag{2.13}$$

The voltage V(t) is terefore the superposition of two exponential functions of diffrent signs. According to equation 2.13 ,the negative root leads to a larger time constant $1/\alpha_1$ than the positive one,which is $1/\alpha_2$. A graph of V(t) is shown in figure 2.4.

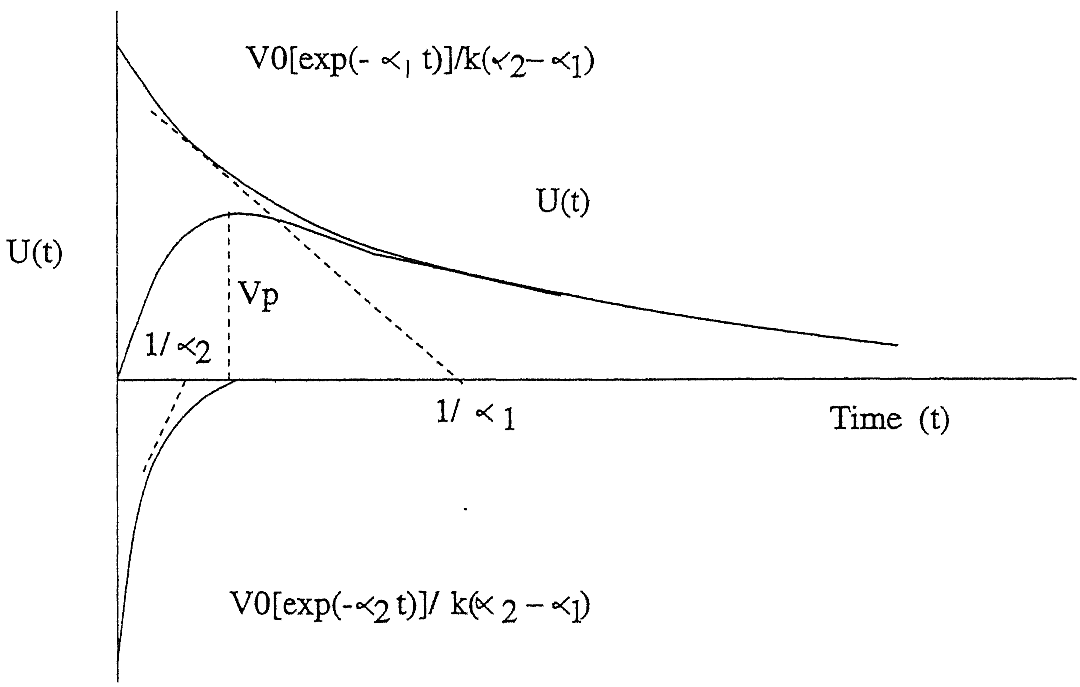


Figure 2.4: Impulse voltage wave and its components

The efficiency of the circuit is defined as

$$\eta = \frac{V_p}{V_0} \tag{2.14}$$

Where V_p is the peak value of the impulse voltage. It can be calculated by finding t_{max} from $\frac{d(V(t))}{dt} = 0$;

$$t_{max} = \frac{ln(\alpha_2/\alpha_1)}{(\alpha_2 - \alpha_1)} \tag{2.15}$$

Substituting this value in the equation 2.15 we get,

$$\eta = \frac{\left(\frac{\alpha_2}{\alpha_1}\right)^{\left[-\frac{\alpha_1}{(\alpha_2-\alpha_1)}\right]} - \left(\frac{\alpha_2}{\alpha_1}\right)^{\left[-\frac{\alpha_2}{(\alpha_2-\alpha_1)}\right]}}{k(\alpha_2 - \alpha_1)} \tag{2.16}$$

We have,

$$\alpha_1\alpha_2 = b \; ; \alpha_1 + \alpha_2 = a \; ; \tag{2.17}$$

By substituting values of a and b from equation 2.9 and 2.10 we get

$$k = R_1C_2 = \frac{1}{2}\left(\frac{\alpha_1+\alpha_2}{\alpha_1\alpha_2}\right)\left[1 - \sqrt{1 - 4\frac{\alpha_1\alpha_2}{(\alpha_2+\alpha_1)^2}\left(1+\frac{C_2}{C_1}\right)}\right] \tag{2.18}$$

Again since $C_2 \ll C_1$ and $\alpha_2 >> \alpha_2$ we get

$$k = \frac{\left(1+\frac{C_2}{C_1}\right)}{(\alpha_1+\alpha_2)} \tag{2.19}$$

Substituting this in the equation 2.16, we get

$$\eta = \frac{C_1}{(C_2+C_1)} = \frac{1}{1+\left(\frac{C_2}{C_1}\right)} \tag{2.20}$$

This equation indicates the reason why the discharg capacitance C_1 should be much larger than the load C_2 Similarly for the circuit of figure 2.3 (a) we get

$$\eta = \frac{C_1}{(C_1 + C_2)} \frac{R_2}{(R_1 + R_2)} \tag{2.21}$$

The unknown resisters R_1 *and* R_2 can be found using equation 2.9 2.10 and 2.17 as:

For circuit figure 2.3 (a) we get

$$R_1 = \frac{1}{2C_1}\left[\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right) - \sqrt{\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right)^2 - \frac{4(C_1 + C_2)}{\alpha_1 \alpha_2 C_2}}\right] \tag{2.22}$$

$$R_2 = \frac{1}{2(C_1 + C_2)}\left[\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right) + \sqrt{\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right)^2 - \frac{4(C_1 + C_2)}{\alpha_1 \alpha_2 C_2}}\right] \tag{2.23}$$

For circuit figure 2.3 (b) :

$$R_1 = \frac{1}{2C_2}\left[\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right) - \sqrt{\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right)^2 \frac{4(C_1 + C_2)}{\alpha_1 \alpha_2 C_1}}\right] \tag{2.24}$$

$$R_2 = \frac{1}{2(C_1 + C_2)}\left[\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right) + \sqrt{\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}\right)^2 - \frac{4(C_1 + C_2)}{\alpha_1 \alpha_2 C_1}}\right] \tag{2.25}$$

All these equations contain the time constants $1/\alpha_1$ and $1/\alpha_2$ which depend on the wave shape. Hence given the value of $T_1/T_2, C_1, C_2$ etc values of R_1 and R_2 can be evaluated.

2.2.2 Multistage Impulse Generator Circuit

The problem of spark gap,physical size of circuit elements and difficulties in supressing corona limit the high voltage used. In order to overcome these difficulties an arrangement where a number of condensers are charged in parallel through high ohmic resistances and

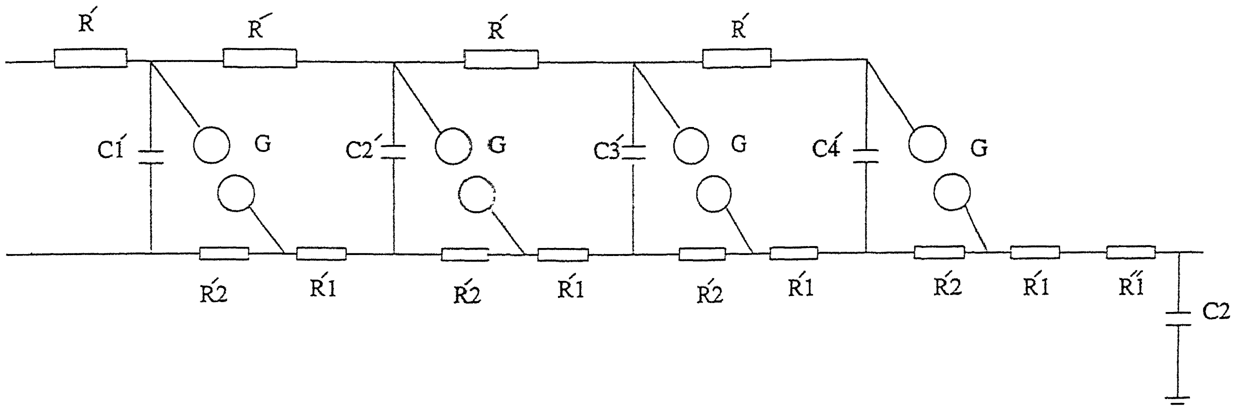


Figure 2.5: A four stage impulse generator circuit

then discharged in series through spark gaps. A typical four stage impulse generator (in laboratory a four stage impulse generator was used) is shown in figure 2.5.

Here,

- R'= Single stage charging resister
- R_1' = Internal front resister
- R_2' = Discharge resister
- $R"_1$ = External front resister
- C_1' = Single stage charging capacitor
- C_2 = Load capacitance

In practice it is necessary to set the distance of the spark gap G_1 only slightly below that of the second and further gaps for earliest breakdown. The axises of the gaps are set in a vertical plane. An ultravoilet illumination from the spark in the first gap irradiates the

other gaps. This ensures a supply of electron released from the gap to initiate breakdown during the short period when the gaps are subjected to overvoltages.

The wavefront control resister R_1 is placed between the generator and load only. This resistance has to withstand the full rated voltage and therefore is inconviently long. This disadvantage can be overcome if either a part of this resistance is distributed or if it is completely distributed within the generator. The charging resisters R' are always large compared to the distributed resisters R'_1 and R'_2. Adding the external front resister $R"_1$ helps to damp oscillations. It is seen that this circuit can be reduced to a single stage impulse generator circuit shown in figure 2.3 (b).

Here,

$\frac{1}{C_1} = \sum \frac{1}{C'_1}$

$R_1 = R"_1 + \sum R'_1$

andeffective discharge resistance R_2

$R_2 = nR'_2 = \sum R'_2$

where n is the number of stages.

2.2.3 Design and Operation of Trigatron

Trigatron is a device which produces initiating elecrtons for breakdown of the spark gap. The trigatron consists of a three electrode gap. The main electrodes which are HV and ground electrode, may be sphere, hemisphere or other homogenous electrode

configurations. A small hole is drilled into the earthed electrode into which a metal rod is projected. The annular gap between the rod and the surrounding sphere is typically about 1 mm. The metal rod or trigger electrode forms the third electrode. It is connected to earthed electrode through a high resistance. A tripping pulse may be given between these two electrodes. A glass tube is fitted across the rod and is surrounded by a metal foil connected to the potential of the main electrode. The function of this tube is to promote corona surface discharge arround the rod as this causes photoionisation of the pilot gap,if a tripping pulse is applied to the rod. Due to this photoionisation enough primary electrons are available in the annular gap which breaks down without appreciable time delay. The glass tube may also fill the annular gap so that the rod as well as the tube with its face is flush with the outside surface of the sphere. Thus a surface discharge is caused by the tripping pulse. Trigatron requires a pulse of some kV,typically $\ll -10kV$. The tripping pulse should have a steep front with steepness $> 0.5kV/ns$ to keep the jitters of the breakdown as small as possible. The outline of the trigatron is given in figure 2.6.

2.2.4 Measurement of Impulses Voltages

The measurement of impulse voltages even of short duration presents no problem, if the voltage levels are of the order of kV. Tremendous developement related to the technique of common CROs and fast ADC circuitsprovide instruments with high bandwidth and possibility to display short duration single phenomena make it possible to measure impulse

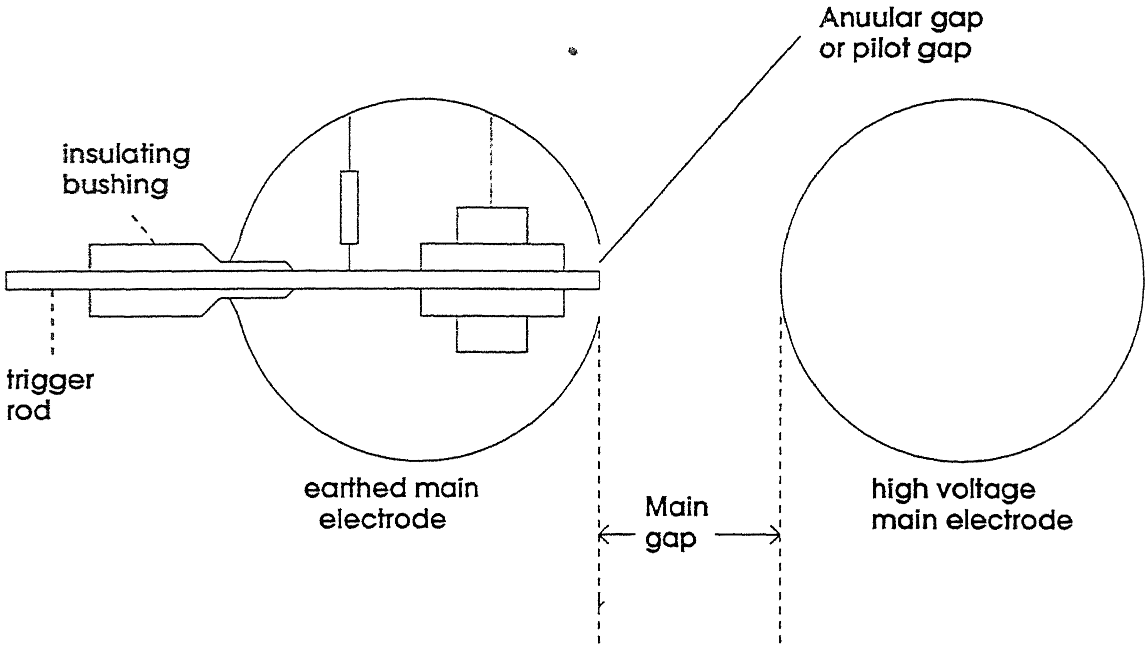


Figure 2.6: The trigatron spark gap

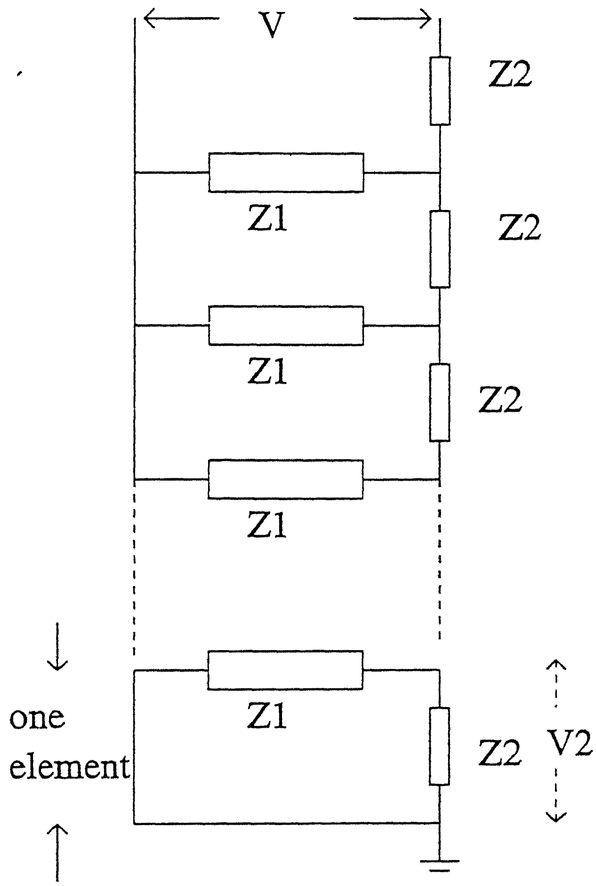


Figure 2.7: A typical voltage devider

voltages of a few kV. problem arises with much higher voltages. It is well known that impulse voltages upto MV are used now a days for testing and research. The voltage deviders necessary to measure these high voltages are specialised apparatus. Voltage deviders for dc, ac or impulse voltage may consist of resisters or capacitors or convenient combinations of these elements. Inductors are not used as pure inductance of required value can not be built without having a sufficient low capacitive value. The height of the voltage devider depends upon the flashover voltage. A typical circuit of voltage devider is shown in figure 2.7. The most difficult problem in simulation of octal network of voltage deviders is of inadequate values of stray capacitance. Exact evaluation of stray capacitance is not possible.[2]

Chapter 3

EXPERIMENTAL SETUP

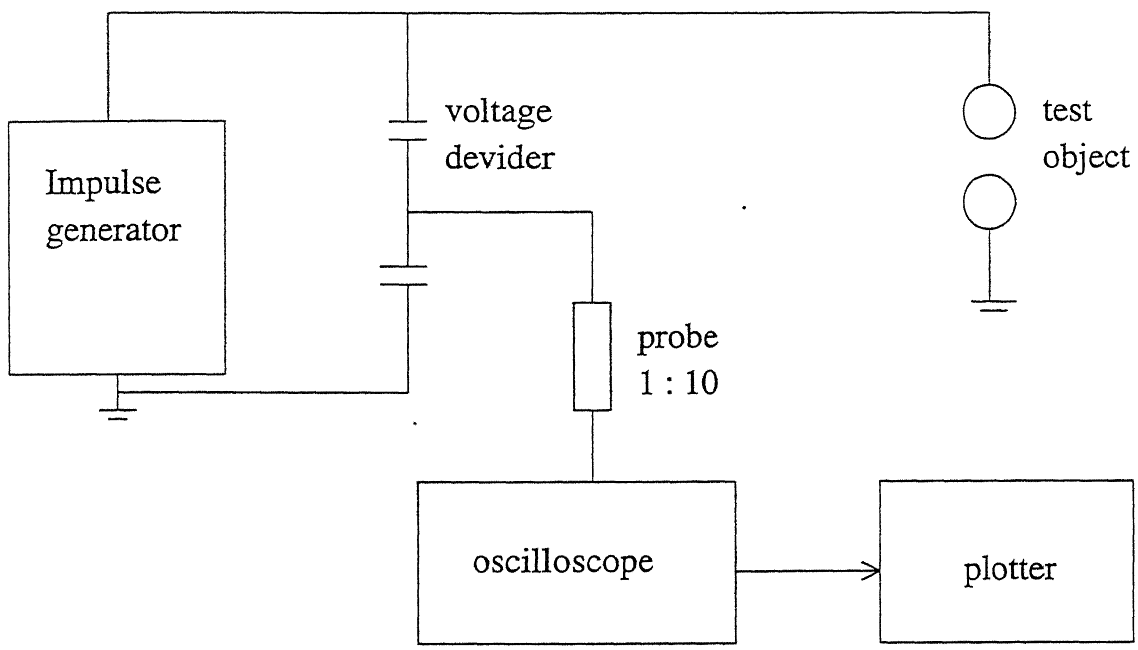


Figure 3.1: Set up of the experiment

The circuit diagram of the setup used is shown in figure 3.1.

3.1 Impulse Generator

A four stage 500 kV 4.4 kJ impulse generator is used for this experimental work. The output of impulse generator is connected to a capacitive voltage devider of ratio 750:1.

Output from this devider is fed to oscilloscope through a probe of ratio 10:1. The total reduction factor between actual voltage applied to test object voltage fed to oscilloscope is 7500:1. Thus voltage reading of oscilloscope multiplied by a factor of 7.5 directly gives the value in kV. The rating of HV capacitor is 1.5 nF,600 kV. The duration between sucessive impulses can be set automatically or they can be provided manually also. a digital storage oscilloscope was used to measure impulse voltage.A digital plotter was connected to oscilloscope to get a hard copy of the plot through RS 232 serial interface.

3.2 Specifications of Impulse Generator used

Technical specifications of the impulse generator used are as follows:

- Maximum charging voltage = 500 kV
- Maximum no load output voltage = 450 kV
- Rated energy = 4.4 kJ
- Number of stages = 4
- Input voltage = 440 kV,3 phase
- Capacitor per stage = 35 nF,125 kV
- Wave shape of li = 1.2/50 microsec

- Wave shape of si = 190/1900, 250/2500 microsec

- Make = TUR,Germany

3.3 Electrode Preparation

The shape and size of the electrodes fabricated for this study were spheres of diameter 40,30,25 and 15 mm made of stainless steel. The shank to hold these electrodes was made of brass having diameter of 8 mm and length of 10 cm. To hold the electrodes a stand of PVC was built. There were arrangements to change the gap between the electrodes.

Before starting the experiments, the electrodes were first cleaned with Acetone and then dried with a soft cloth. The surface finish of the electrode was found to deteriorate due to breakdown, hence process of polishing, electroplating and cleaning had to be done repeatedly for a number of times. The whole electrode arrangement had to be protected from dust.

Chapter 4

THEORY OF BREAKDOWN BY IMPULSE VOLTAGES

4.1 Classification of Electric Field

The qualitative definition of electric strength of a dielectric is the maximum electric stress a dielectric can withstand. A quantitative definition is however complicated as many factors like pressure,humidity,temperature, electrode shape and size,voltage waveform and presence of impurities etc greatly affect the breakdown strength of a dielectric.

The elecric field configurations are classified between two extreme forms of field.

(i) Uniform

(ii) Extremely non uniform field

In a uniform field the potential is linearly distributed and the electric field intensity is constant throughout the space between the electrodes. An important characteristic of uniform field is that the breakdown takes place without any partial discharge preceeding

the breakdown.

There is an extreme non linear distribution of potential in space between two needle electrodes leading to strong non uniformity in electric field intensity. This type of field is called extremely non uniform field.

4.2 Degree of Uniformity of Electric Field

The degree of uniformity η,introduced by Schwaiger in 1922, as a measure of uniformity of electric field is defined as follows :

$$\eta = \frac{E_{mean}}{E_{max}} = \frac{U}{d}\frac{1}{E_{max}} \tag{4.1}$$

$$U = E_{max}\eta d \tag{4.2}$$

Where E_{mean} and E_{max} are the peak values of the mean and maximum field intensity respectively. U is the peak value of potential difference applied between the two electrodes at a d distance apart.

Typical values of η for different type of field is given in figure 4.1

4.3 Breakdown Characteristics in Non Uniform Field

Since the partial discharge (PD) inception and breakdown voltage in weakly non uniform field are equal, the breakdown can be estimated from equation 4.3

$$U_i = U_b = E_{max}d\eta \tag{4.3}$$

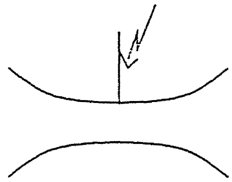
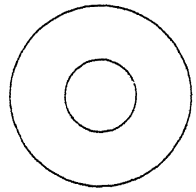
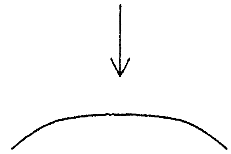
field configuration	uniform	weakly non uniform	extremly non uniform
typical electrode configuration			
η	1.0	$0.01<\eta<0.2$	$\eta<<0.01$

Figure 4.1: limits of eta for dirrerent fields

The value of E_{max} in case of weaky non uniform field is always higher than electric strength E_b in uniform field. The breakdown strength mainly depends upon the value of η. The η factor can be found from an empirical formula for sphere-sphere configuration :

$$E_{max} = 0.9\frac{U}{2d}\left(2+\frac{d}{r}\right) \tag{4.4}$$

$$E_{mean} = \frac{U}{d} \tag{4.5}$$

$$\eta = \frac{2}{0.9\left(2+\frac{d}{r}\right)} \tag{4.6}$$

If the measured values of U_b-d characteristic are known,E_{bmax}-d characteristics can be calculated. These curves for a sphere-sphere configuration are drawn in figure 4.2. From these curves it is evident that E_{bmax} does not change much within a certain range of gap distance d .[1]

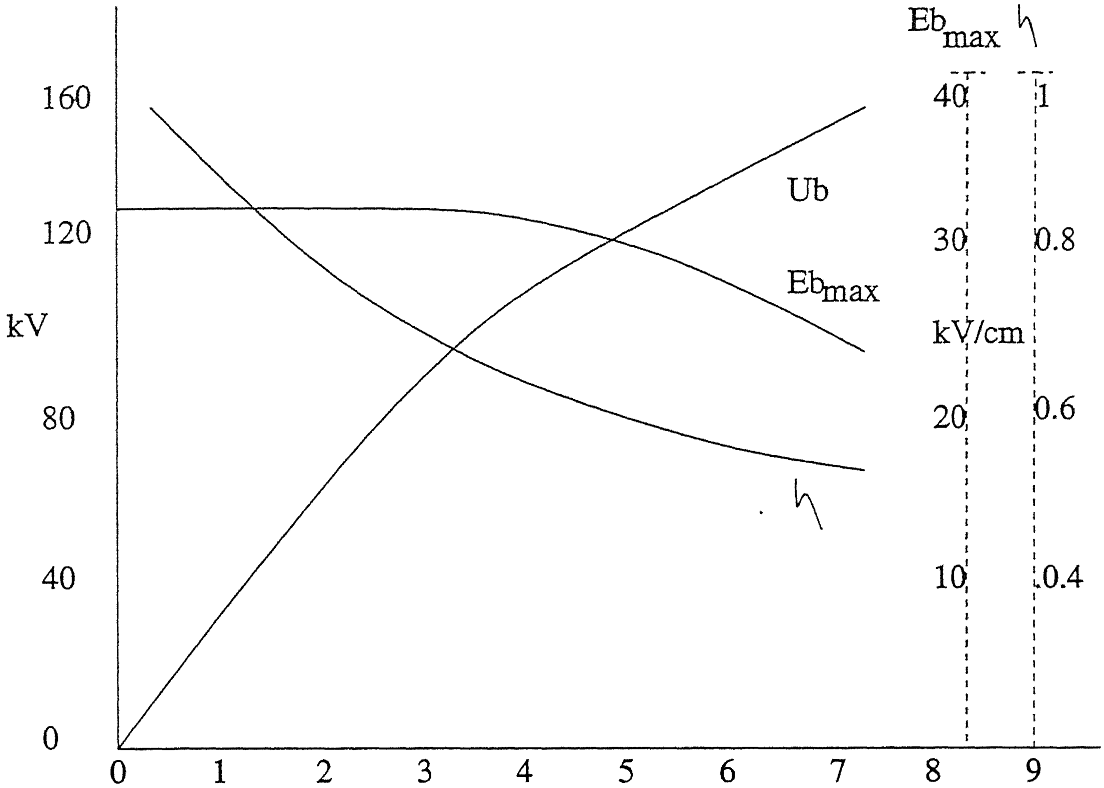


Figure 4.2: Variation of U_b, E_{b-max} and η with gap distance

4.4 Discharge in Non Uniform Field : Effect of Polarity

In non uniform fields condition for the developement of discharge are altogether different from those of uniform field. In non uniform field, if the voltage between the electrodes increases sufficiently slowly,long before the formation of corona sufficiently intensive ionisation will take place in the immediate vicinity of the electrodes, Volume charges created by the primary ionisation exert considerable influence on ther process of further developement of the discharge. The initial ionisation in the non uniform field will develope in the region of strongest field,i.e. at the needle and the distortions of the field will be different

for positive and negative polarities of the needle.

With positive polarity of the point an electron formed in the gap,while moving towards the point, falls in the region of strong field, starts ionising and forms an electron avalanche. If voltage between electrodes increases slowly sufficiently large number of such avalanches can be formed. When each of these avalanches reaches the point electrode, electrons of the avalanches go away into the point electrode,positive ions remain in the space moving slowly towards the opposite plane electrode. Thus near the point electrode positive volume charge is formed. The field produced by this volume charge is opposite to the applied field. Presence of poitive volume charge decreases the field intensity in the vicinity of the point and slightly increases it in the external space. Further ionisation in the vicinity of the point is weakened and this makes fulfillment of the condition for self-sustenance of discharge difficult.

With negative polarity of the point electrons formed on the surface of cathode immediately fall in a strong field and form avalanches which move towards the plane electrode. When electrons of the avalanche get away from the region of strong field,they cease to produce ionisation travel towards the anode. A part of them reaches the anode and is neutralised there; and remaining part is arrested by oxygen atoms with the formation of negative ions, after which velocity of movement of negative charges towards the anode decreases sharply. Positive ions of the avalanches gradually move away to the point, but

as their velocity is small there is always positive volume charge in the immediate vicinity of the point electrode. Thus in the vicinity of the point there is a highly compact positive volume charge and in the depth of the gap a dispersed negative charge. Because of its small density, the negative volume charge does not exert considerable influence on the external field. But the positive volume charge distort it such that the field intensity in the vicinity of the point electrode increases and the fulfilment of the condition of discharge is made easy.

From above analysis it follows that the voltage of the appearance of corona in the point plane gap with positive polarity must be greater than that with negative polarity.

If the point electrode is positive and voltage between them is sufficiently high, an avalanche begins on the right hand side of the volume charge which, mixing with the positive ions of the volume charge create anode streamer filled with plasma. The charges of the plasma are situated in an electric field , therefore they are distributed unequally. There are surplus positive charge on the head of the streamer. This charge partly compensates the field in the canal of the streamer itself and creates increased intensity at its head. Presence of a region of stronge field before the head ensures formation of new avalanches. These newly formed avalanches convert this volume charge into a canal of streamer and breakdown of the dielectric becomes easier.

If the polarity of the point electrode is negative, formation of the streamer in the

vicinity of the point electrode becomes very difficult. A strong field near the rod helps the formation of a large number of avalanches spreading in the direction of the positive volume charge surrounding the point. Just because of a large number of simultaneously developing avalanches, condition of formation of a narrow canal filled with plasma do not exit. A layer of plasma is formed which acts as a screen. The field intensity due to this screening effect comes down in the region immediately after the point electrode . If the voltage is further increased ionisation continues to take place for a long time in the space between the point and the plasma layer which gradually increases in volume is slightly stretched towards the opposite electrode. Field intensity on the outer surface of the plasma layer increases gradually and, if voltage is further increased, an avalanche of electrons originates on the right hand side of this layer. Positive charges of these avalanches give rise to further increase of intensity at the boundary of the plasma layer because of which a large number of new avalanches appear. The merging of these avalanches leads to lenthening of plasma layer and its conversion into streamer. Therefore breakdown strength with the negative point is considerabley higher than that with positive point.[2]

4.5 Time Requirements for Formation of Breakdown

With high voltages,especially with pulses of very short duration, it is possible that breakdown may not occur even when the peak voltage magnitude exceeds the lowest breakdown

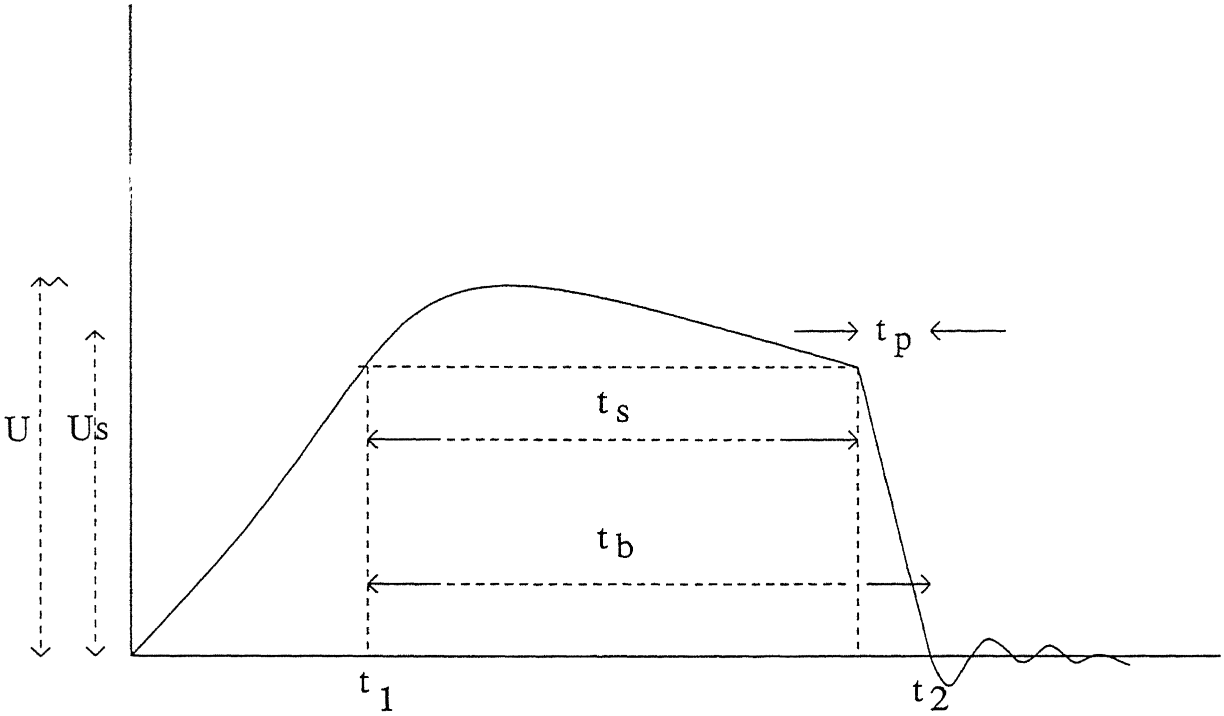


Figure 4.3: Duration of statistical time and propagation time

voltage,unless the presence of sufficient number of initiatory electrons is ensured. This is called statistical time lag t_s or a time delay in beginning the discharg process with impulse voltage. The statistical time lag t_s depends upon the area of electrodes,the gap distance and magnitude of radiation producing primary electrons.

Once the discharge process has begun,it requires a certain finite time called 'propagation time' to reach the opposite side electrode. The total propagation time in a gap dependsthe individual type of PD and their extent in the gap just before the breakdown. The extent of PD depends upon the field distribution and magnitude of applied voltage. For streamer discharge the propagation velocity is about 100 cm/μs and for leader discharge it is less than 10 cm/μs. Since breakdown in very very long gaps is achieved when

a stable leader bridges the gap, the transient time required for propagation is mainly determined by the leader propagation velocity.

A typical shape of impulse voltage is shown in figure 4.3.

- t_s = statistical time lag
- t_b = Total time required for formation of breakdown
- t_p = Propagation time

here $t_b = t_s + t_p$

The occurance of breakdown is conditional. The duration of applied voltage magnitude above U_s must prevail longer than the minimum time required for the formation of breakdown. The probability of breakdown for a given impulse voltage is estimated experimentally. A large number of identical impulses are applied on a gap. The ratio of number of pulses accomplishing breakdown to the total number of pulses applied gives the probability of breakdown. U_{b-100} represents the 100% breakdown. U_{b-50} is the 50% breakdown voltage, that is , only half the number of applied impulses of this magnitude accomplish breakdown.

Let an impulse voltage of same wave shape and different peak value is applied across a gap. This is shown in figure 4.4. Let for an impulse voltage shape 1, the breakdown occures at the time t_1. As the voltage level is increased it is observed that the instant of

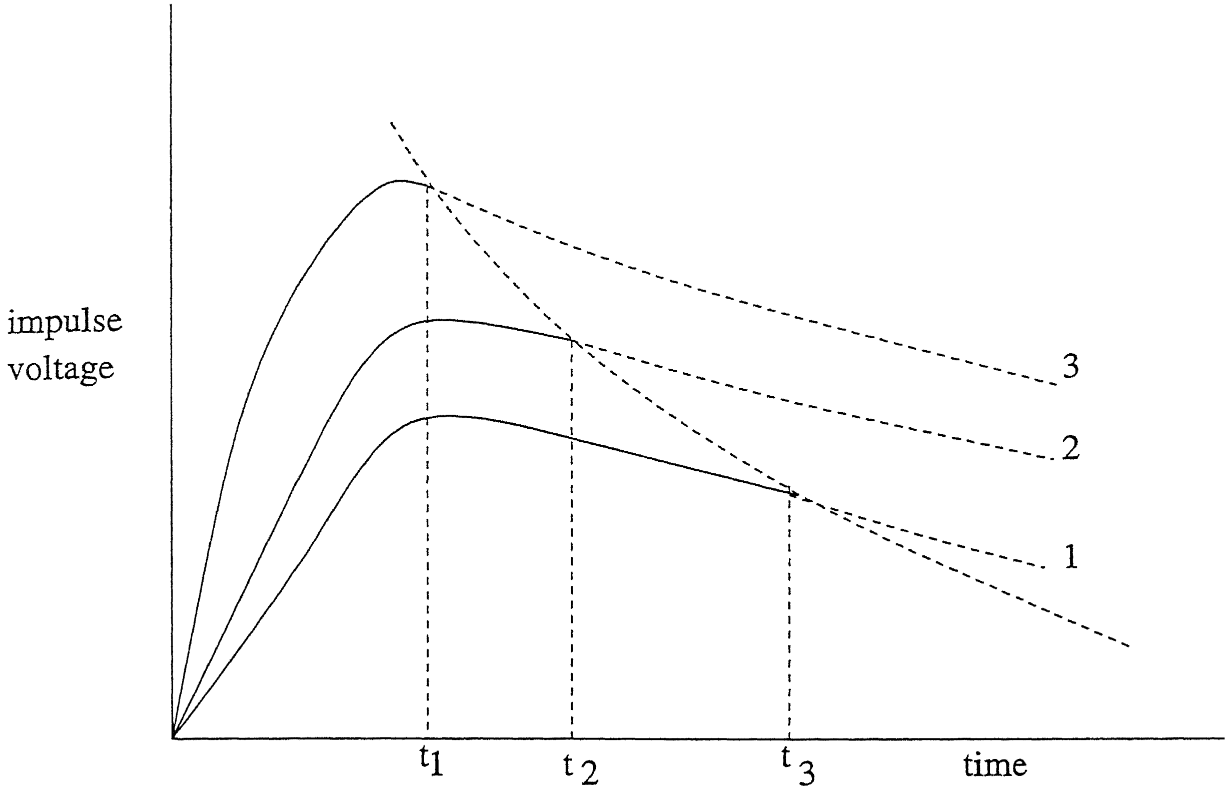


Figure 4.4: Breakdown voltage time characteristics for impulse voltage

breakdown shifts towards left and breakdown occures at a lower time at t_2. If voltage is increased further as in shape 3 the breakdown occurs at even smaller time t_3. If voltage higher than 3 is applied then the breakdown will occur on the front region of the impulse. All experiments are done with the breakdown in the wave-tail region.[1]

Chapter 5

INVESTIGATIONS

With the impulse generator employed in HV lab two wave shapes of switching impulses can be obtained. These two wave shapes are $190/1900\mu s$ and $250/2500\mu s$. The wave shapes are changed by changing the values of internal front resistors R_1 and discharge resister R_2.

5.1 RESULTS WITH POSITIVE POLARITY SWITCHING IMPULSE

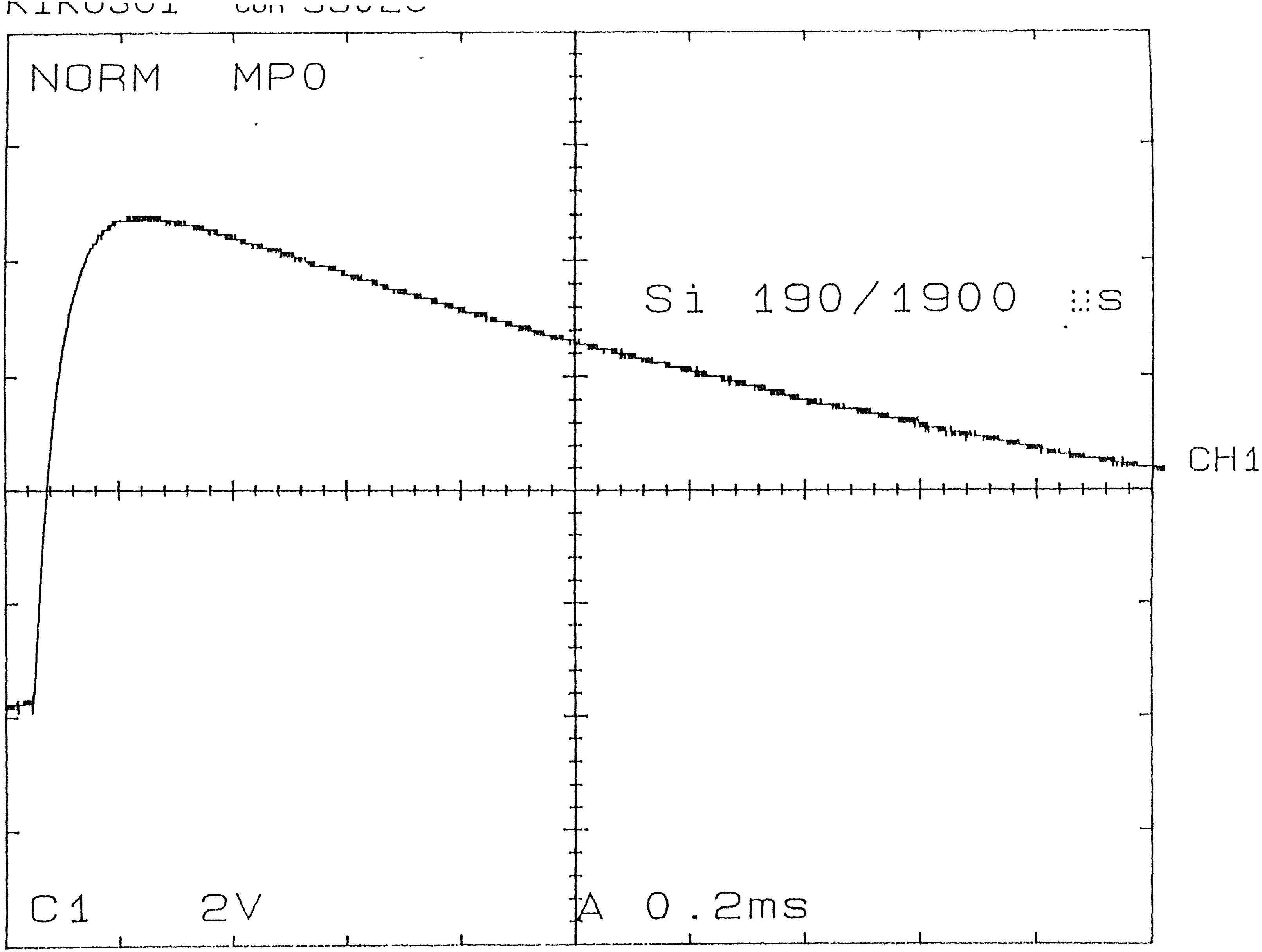
5.1.1 Results With $+190/1900\mu s$ Switching Impulse

The switching impulse of $190/1900\mu s$ is obtained by using internal front resistor $R_1 = 20.4\ k\omega$ and discharge resistance $R_2 = 27.2\ k\omega$ single stage charging capacitance is 35 nF. The load capacitance used is 1.5 nF , 600 kV. Experimental arrangement is set up as in fig 3.1.

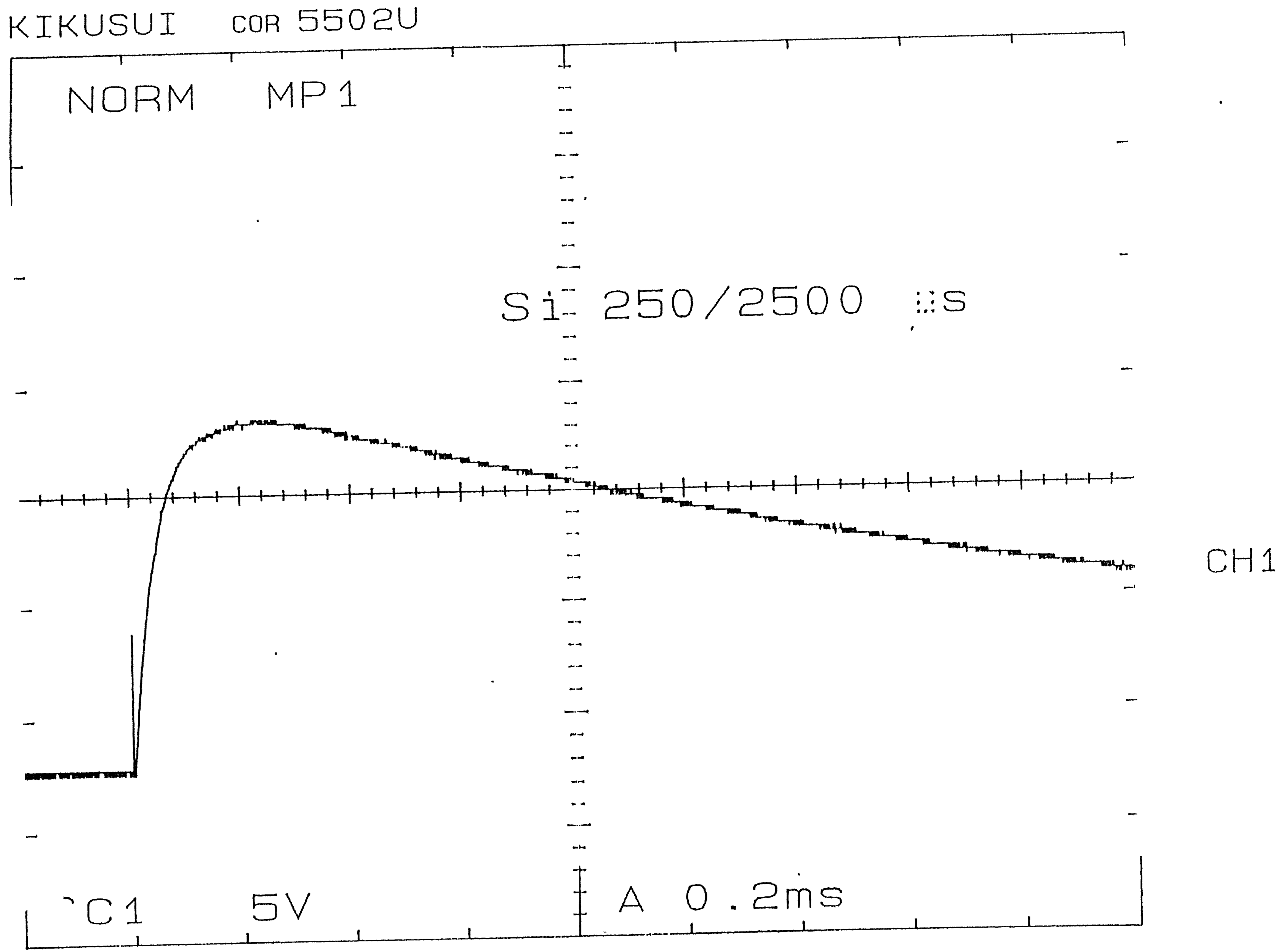
Voltage level is raised gradually not exceeding the limit 1 kV/sec. A rough estimate

for distance between the spark gap of impulse generator is obtained as follows. The test object is sphere-sphere configuration for which breakdown strength is arround 20 kV/cm. For a gap distance of 10 cm between the test object we require arround 200 kV for breakdown to take place. It means each stage should produce 50 kV (as there are four stages). Spark gap configuration is also a sphere-sphere configuration for which breakdown strength is arround 25 kV/cm (as sphere diameter of spark gap is large and gap distance is less compared to test object , the field between the spark gap is more uniform compared to field between test object. Hence breakdown strength is assumed to be 25 kV/cm instead of 20 kV/cm). For 50 kV to be produced by each stage a spark gap of arround 2 cm (20 mm) is to be set. First of all spark gap is set a little less than this rough estimated value. Now voltage is raised. When voltage reaches near the required value breakdown takes place between the spark gap. Now the gap distance is increased slightly and again voltage is increased. If breakdown between the test object does not take place gap distance between spark gap is further increased and voltage is raised. This process is repeated until breakdown takes place between the test object. Now voltage level is increased slightly so that out of 20 pulses applied breakdown takes place 10 times. This value of the voltage corresponds to U_b value.

Important precaution while setting the voltage level is that the breakdown should take place between all the four stages of impulse generator and applied voltage is not greater



Oscillogram showing a Si of +190/1900 us



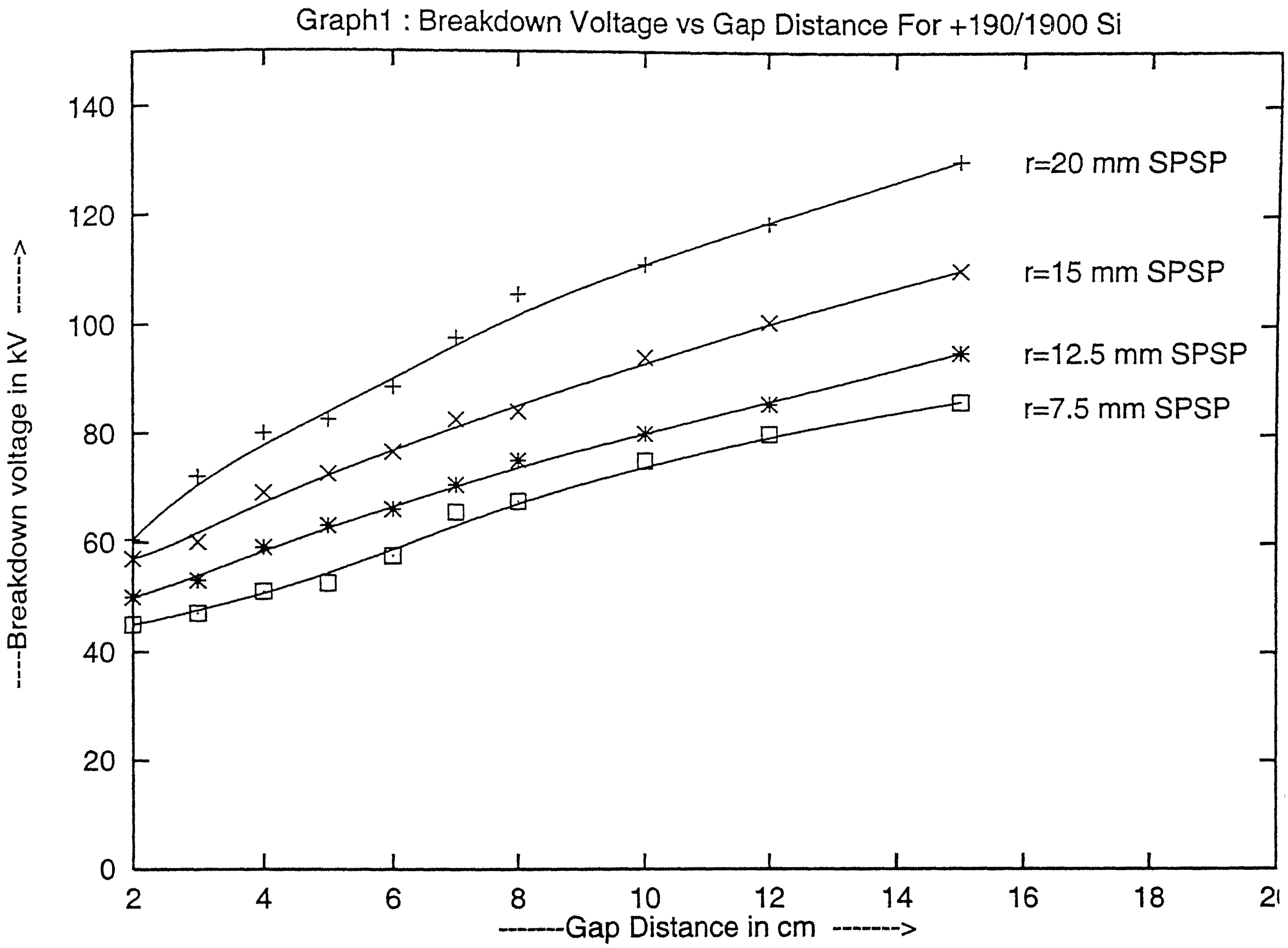
Oscillogram showing a Si of +250/2500 us

Gap Distance cm	Breakdown Voltage (kV)			
	r=20mm	r=15mm	r=12.5 mm	r=7.5 mm
2 cm	60.5	57.0	50.0	45.0
3 cm	72.0	60.0	53.0	47.0
4 cm	80.8	69.0	59.0	51.0
5 cm	82.5	72.5	63.0	52.5
6 cm	88.5	76.5	66.0	57.5
7 cm	97.5	82.5	70.5	65.5
8 cm	105.5	84.0	75.0	67.5
10 cm	111.0	94.0	80.0	75.0
12 cm	118.5	100.5	85.0	80.0
15 cm	130.0	110.0	95.0	86.0

Table1 : Data for breakdown voltage for +190/1900 us Si

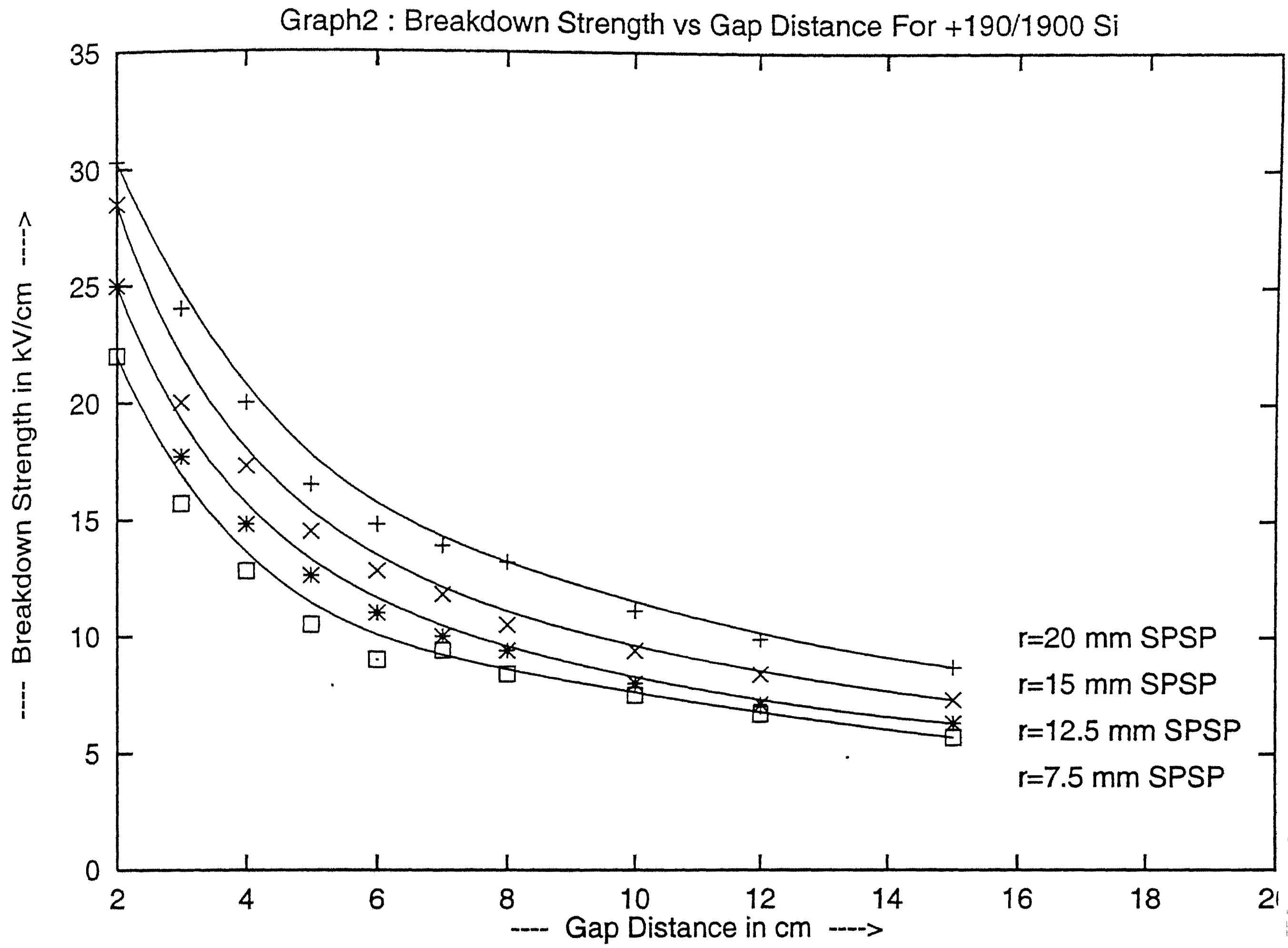
than U_{b-100} (i. e. breakdown should not take place 20 out of 20 pulses applied).

In this study four test object configurations all sphere-sphere of radius 20mm, 15 mm, 12.5mm and 7.5mm are selected. For each configuration gap distance is varied from 2 cm to 15 cm. The gap distance so changed changes the field from uniform to weakly non uniform field gradually. This way it becomes possible to study how the behaviour of dielectrics changes as one moves from uniform field to weakly non uniform field. For each electrode configuration the value of U_{b-50} is obtained at various gap distances. The values of U_{b-50} for $190/1900\mu s$ impulse is shown in table 1. The least square approximated graphs are plotted in graph 1. Important observation is that at a small gap distance the difference between the breakdown voltage is small for different field configurations. This difference keep on increasing as gap distance is increased. It implies that as field is approaching towards more uniform field all electrode configurations give same breakdown



voltage. If graphs are extrapolated then all graphs tend to meet at a breakdown strength of 30 kV/cm. This establishes that the breakdown strength of air in uniform field is arround 30 kV/cm.

Breakdown strength (breakdown voltage/gap distance) vs gap distance graphs for all electrode configurations are plotted in graph2. Here important observation is that breakdown strength is maximum when field is uniform and decreases as field becomes non uniform. For a same gap distance the configuration having larger sphere diameter



has more uniform field that is why graph of larger sphere diameter is above the graph of smaller diameter in graph2.

5.1.2 Results With $+250/2500\mu s$ Switching Impulse

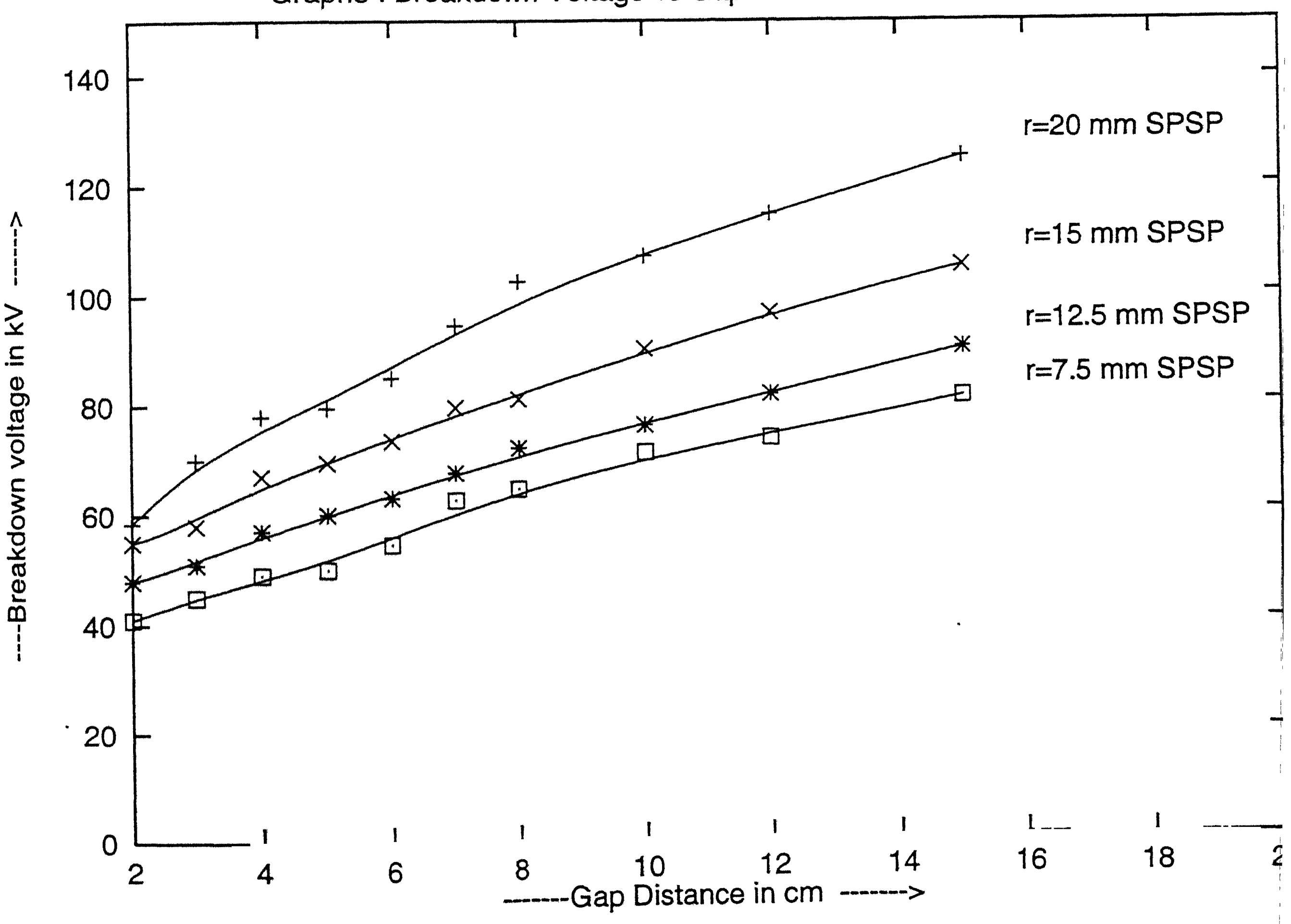
The switching impulse of $250/2500\mu s$ is obtained by using internal front resistor $R_2' =$ 20.4 $k\omega$ and discharge resistance $R_2' = 54.4\ k\omega$. The single stage capacitance is 35 nF and load capacitance is 1.5 nF ,600 kV.

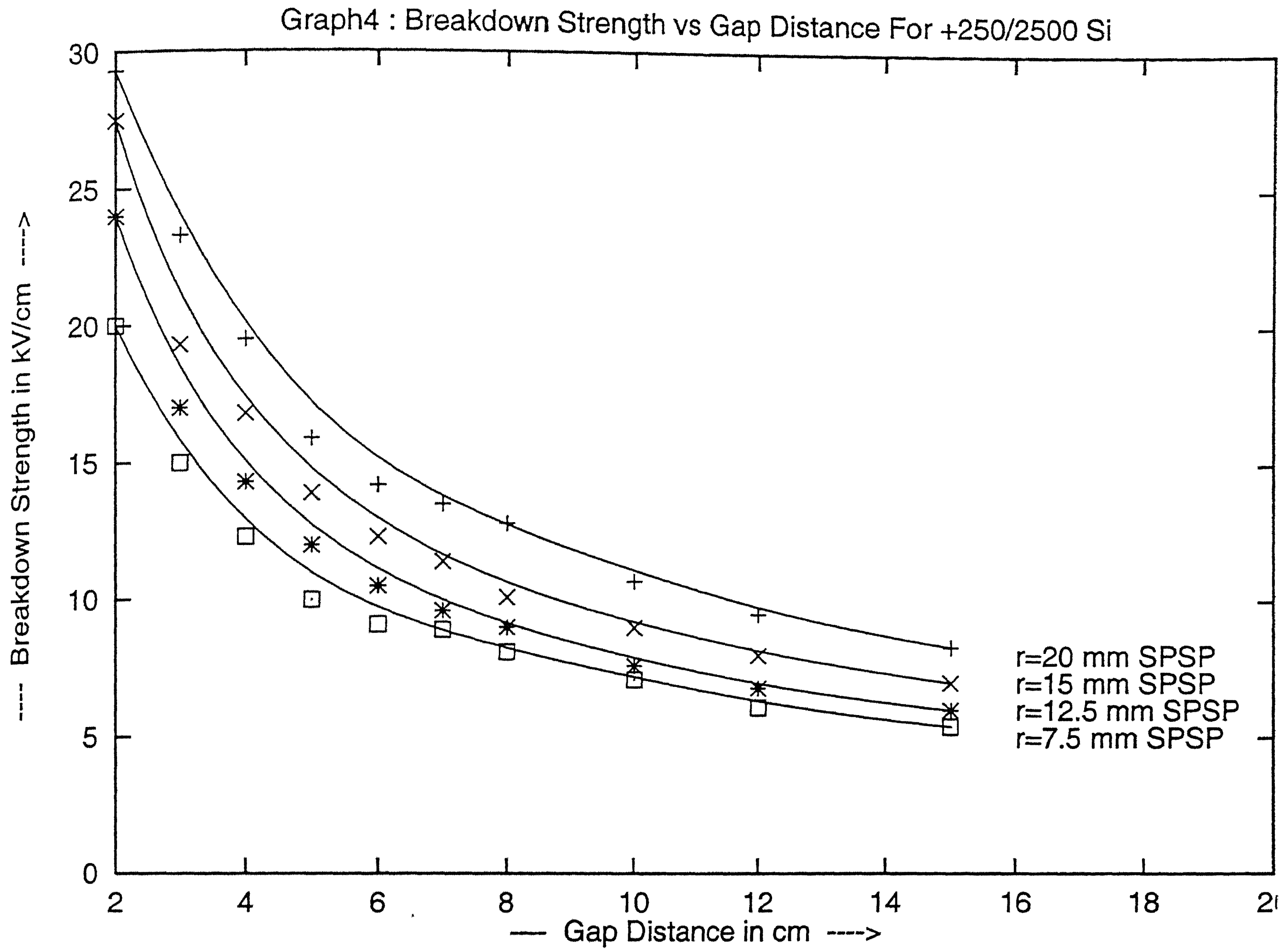
The procedure is adopted as in previous article to set the voltage level. Here also

Gap Distance	Breakdown Voltage (kV)			
cm	r =20 mm	r =15 mm	r =12.5mm	r =7.5 mm
2	58.5	55.0	48.0	41.0
3	70.0	58.0	51.0	45.0
4	78.0	67.0	57.0	49.0
5	79.5	69.5	60.0	50.0
6	85.0	73.5	63.0	54.5
7	94.5	79.5	67.5	62.5
8	102.5	81.0	72.0	64.5
10	107.0	90.0	76.0	71.0
12	114.5	96.5	81.5	73.5
15	125.0	105.0	90.0	81.0

Table2 : Data for breakdown voltage for +250/2500 us Si

Graph3 : Breakdown Voltage vs Gap Distance For +250/2500 us Si





the gap distance is varied from 2 cm to 15 cm. The breakdown voltage for various gap distance is measured for all four electrode configurations. These graphs are shown in graph3. Nature of the graphs is same as that for 190/1900 microsecond impulse As gap distance is increased there is an increase in the breakdown voltage. Like the 190/1900 microsec impulse difference in the breakdown voltage for different electrode configuration is small when gap distance is small and this difference increases as the gap distance is increased.

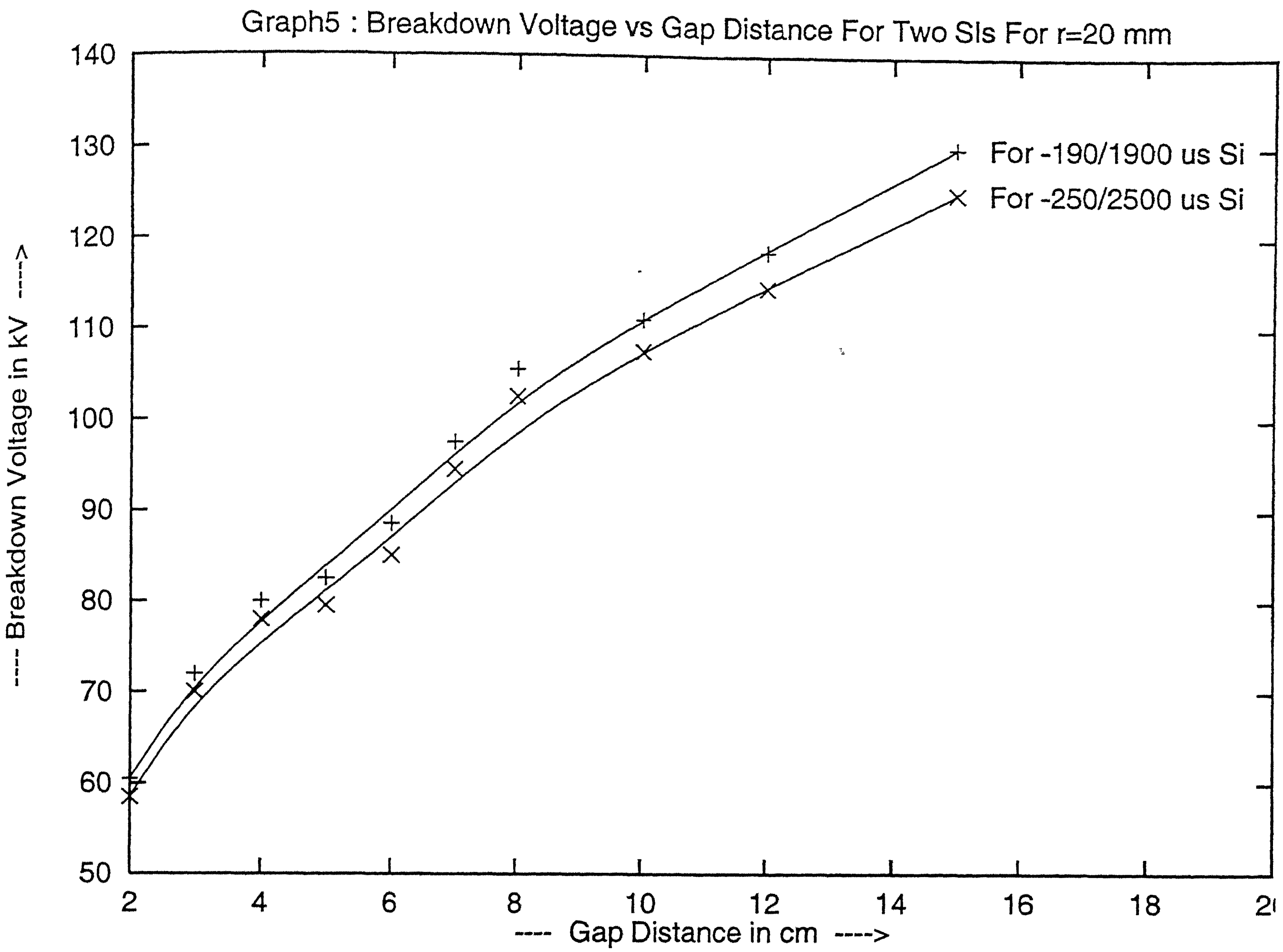
The graphs of breakdown strength vs gap distance for $250/2500\mu s$ impulse are plotted in graph4. Important observation is that the breakdown strength is maximum when gap distance is small (i. e. field is uniform) and it decreases as distance is increased (i. e. field is becoming non uniform).

5.1.3 Comparison of the Results of the Two Switching Impulses

Graphs of breakdown voltage vs gap distance are plotted for two wave shapes (190/1900 microsec and 250/2500 microsec) for all four electrode configurations. These graphs for 20 mm, 15 mm, 12.5mm and 7.5 mm sphere-sphere configurations are plotted in graph5, graph6, graph7, graph8 respectively.

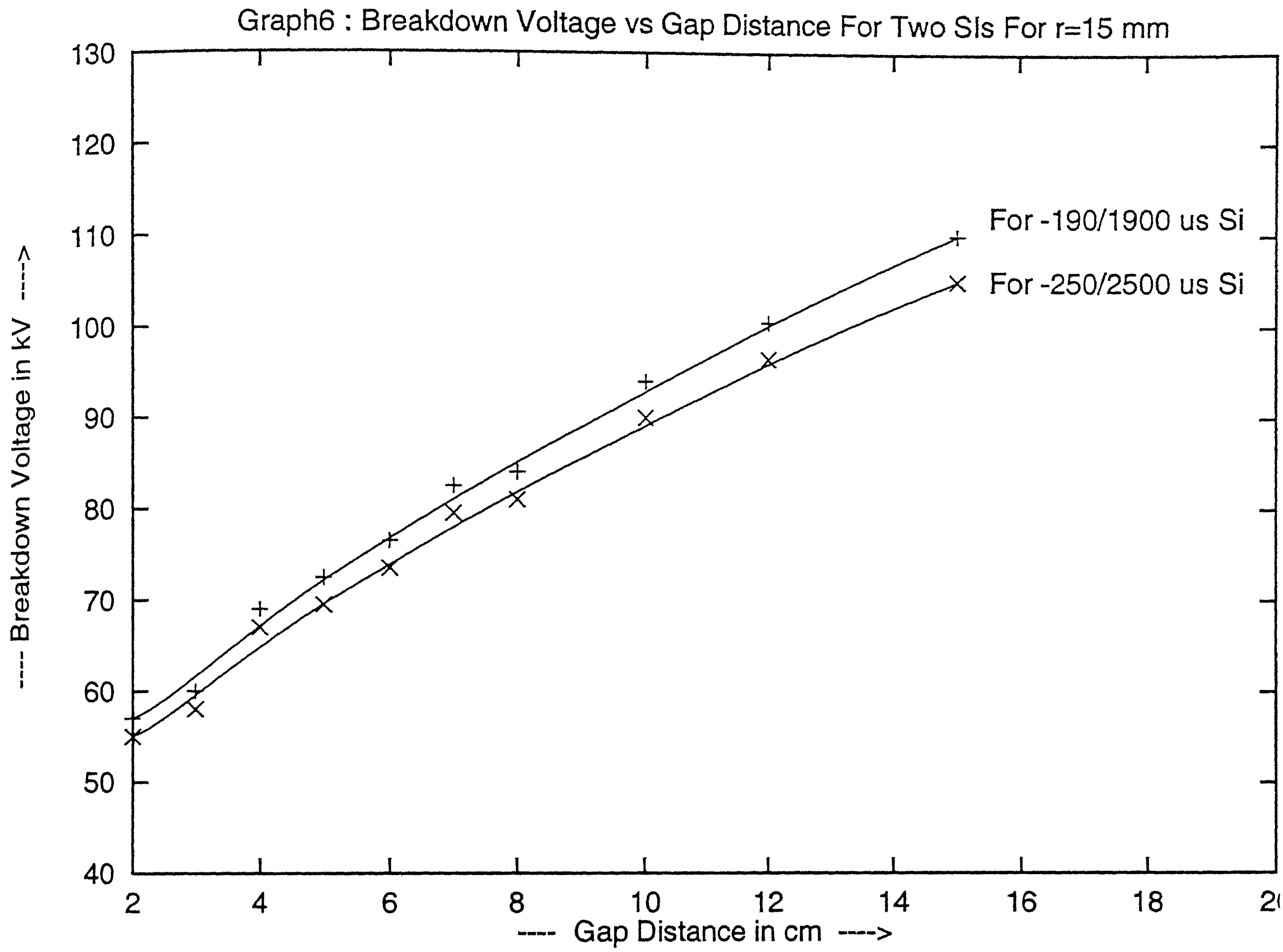
Nature of all these graphs is similar. From each graph it is clear that breakdown voltage for $250/2500\mu s$ impulse is always less than compared to $190/1900\mu s$ impulse for the same gap distance i. e. the breakdown strength of dielectric is always less for $250/2500\mu s$ compared to $190/1900\mu s$ impulse. From these observations it is clear that breakdown strength is closely related to rise time and tail time of the switching impulse. For switching impulse of smaller rise time and tail time breakdown strength is larger compared to switching impulse of larger rise time and tail time.

Another important observation is that difference in breakdown strength for two wave shape is small when gap distance between the electrodes is small (i. e. field is uniform). This difference keeps on increasing as gap distance is increased (i. e. field is made



non uniform). The behaviour of dielectric is closely related to the wave shape of the impulse,when the field between electrodes is non uniform. In uniform field all wave shapes give the same breakdown strength.

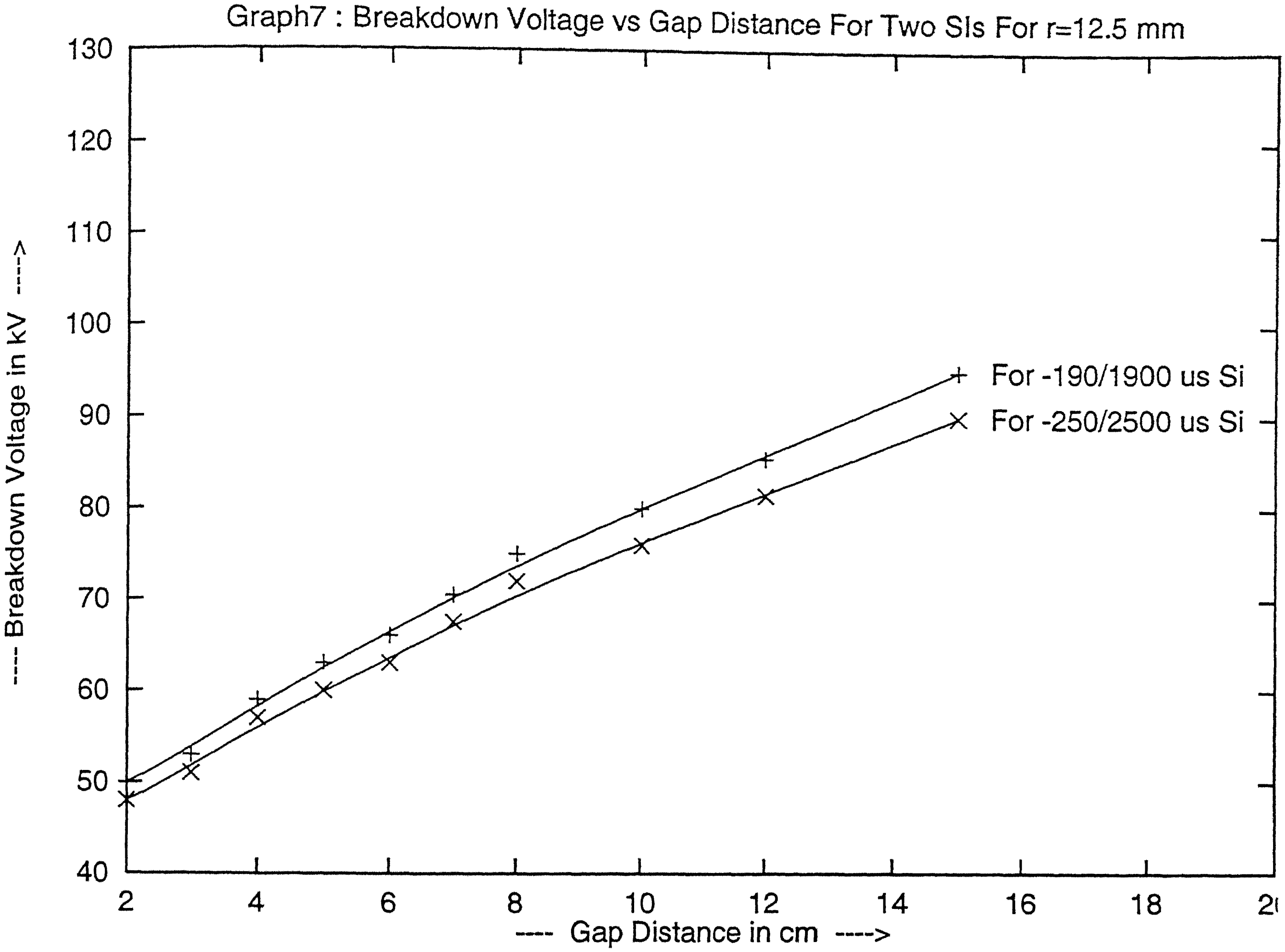
Breakdown strength for 190/1900μs, 250/2500μs and ligthning impulse 1.2/50μs for 20 mm sphere-sphere configuration are plotted against gap distance in graph9. Breakdown strength is maximum for lightning impulse and is minimum for 250/2500μs impulse.



5.2 RESULTS WITH NEGATIVE POLARITY SWITCHING IMPULSES

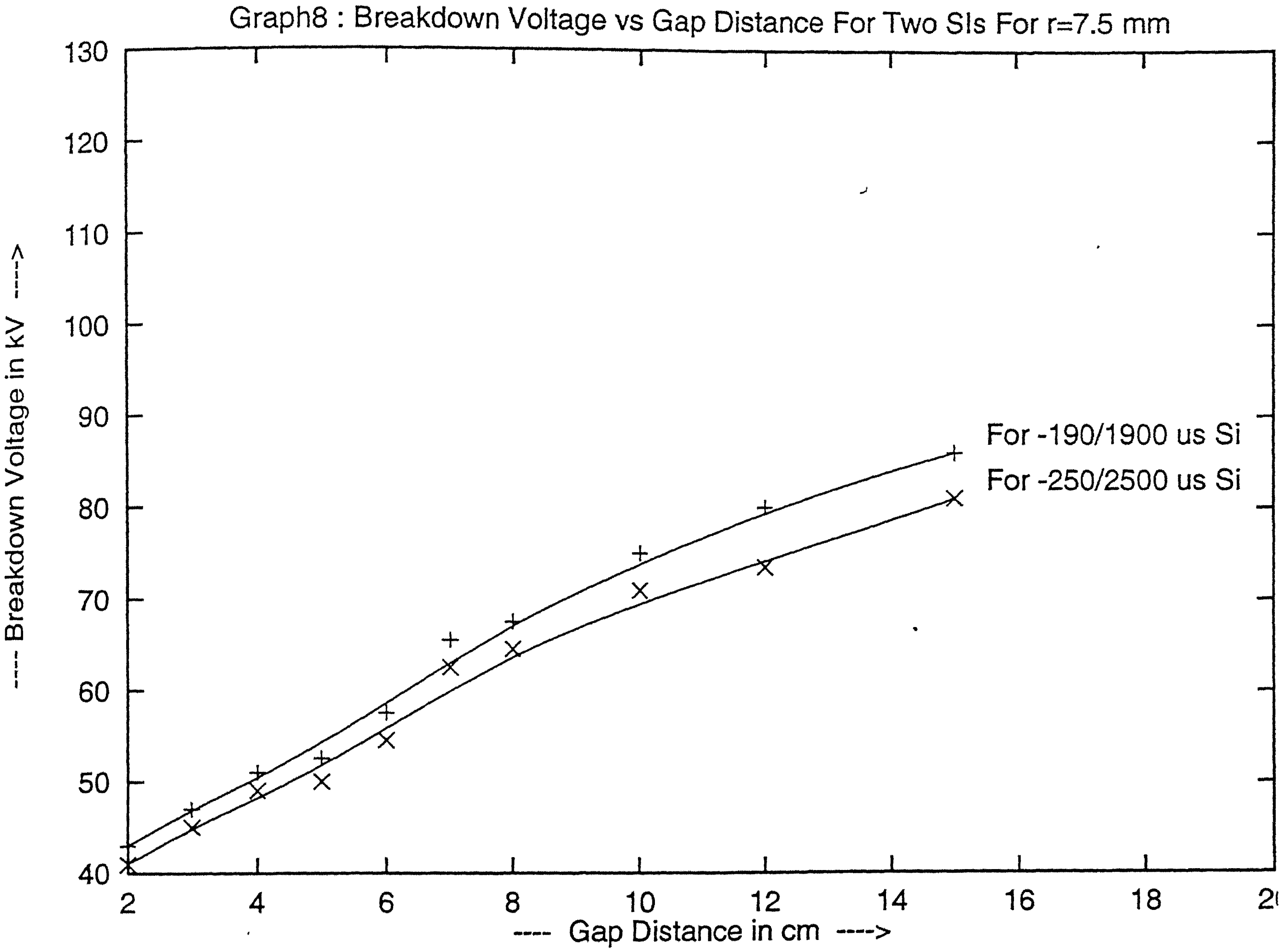
5.2.1 Results With $-190/1900\mu s$ Switching Impulse

Negative switching impulse of $190/1900\mu s$ is obtained by setting internal front resistor $R_1' = 20.4\ k\omega$ and discharge resistor $R_2' = 27.2\ k\omega$. The load capacitance is 1.5 nF, 600 kV. Procedure for setting voltage is same as in section 5.1. Gap distance is varied from 2 cm to 15 cm for all four electrode configurations.The values of breakdown voltage for



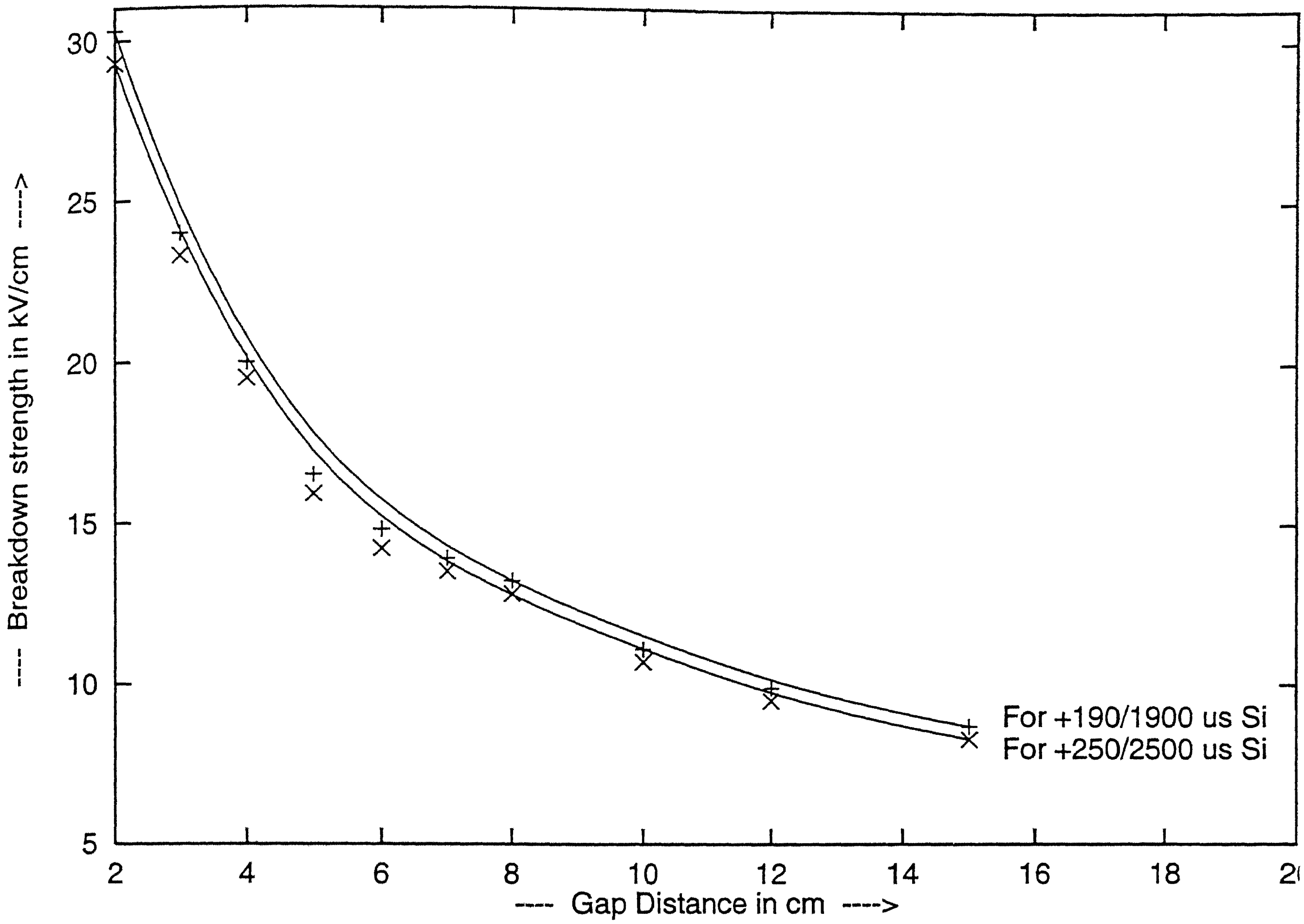
all configurations are shown in table3.

Breakdown voltage vs gap distance graphs for negative polarity $190/1900\mu s$ impulse are shown in graph10. These graphs have same shape as that for positive polarity pulse. Important observation is that breakdown voltage of dielectrics for same electrode configuration is higher for negative polarity compared to positive polarity pulse The reason for this is explained in section 4.4. In case of positive electrode in non uniform field ionisation by electron collision takes place in the field region close to the positive electrode.



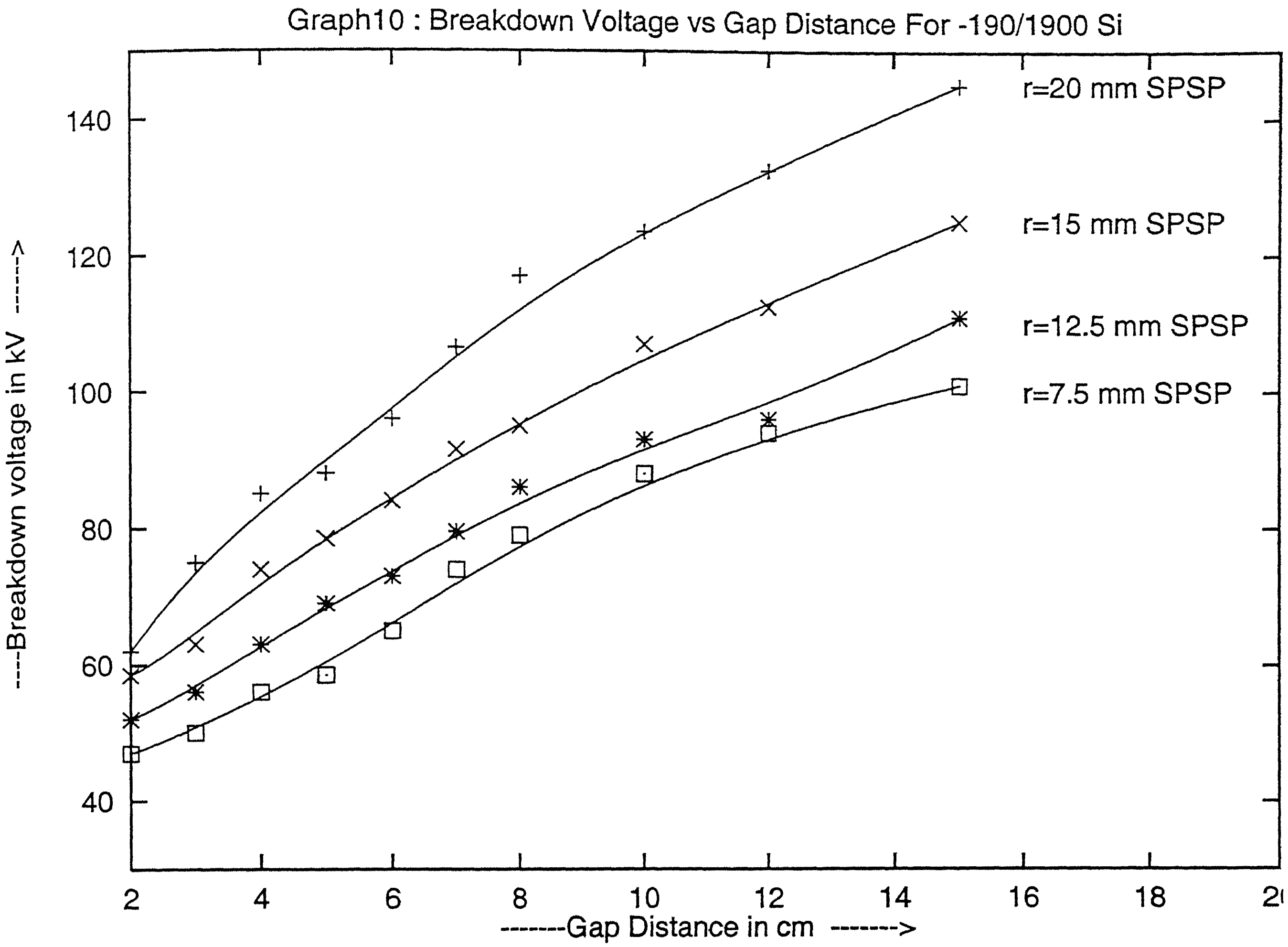
Electrons because of their higher mobility will be readily drawn into the anode leaving the positive space charge behind. The space charge will cause a reduction in the field strength close to the anode and at the same time will increase the field further away from it. The high field region is in time moving further into the gap extending the region for ionisation. The field strength at the tip of the space charge may be high enough for the initiation of a cathode directed streamer which subsequently lead to complete breakdown. With negative electrode, the electrons are repelled into the low field region leaving posit-

Graph9 : Breakdown strength vs Gap Distance For Two SIs for r=20mm



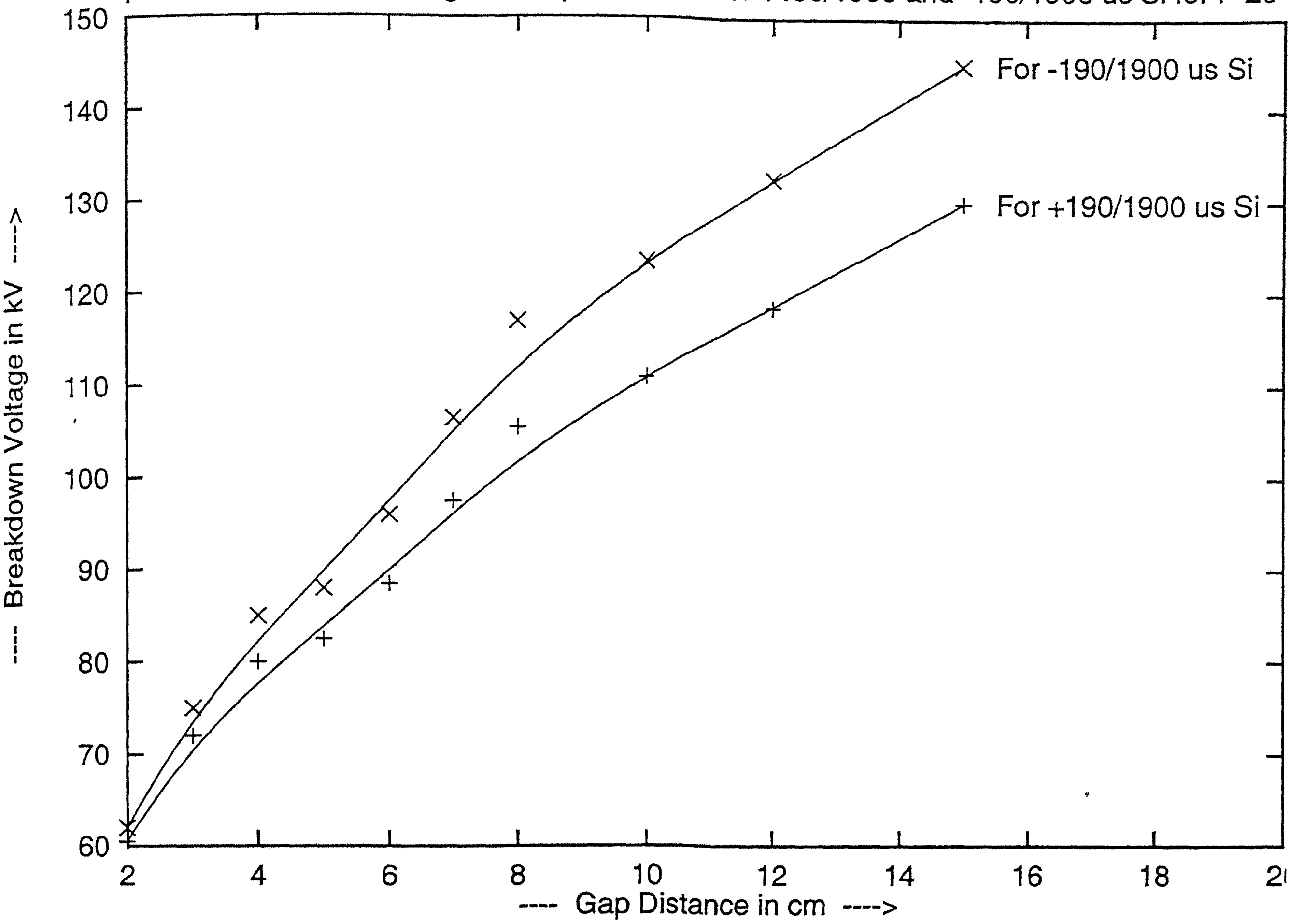
Gap Distance cm	Breakdown Voltage kV			
	r = 20mm	r = 15 mm	r=12.5 mm	r= 7.5 mm
2	62.0	58.5	52.0	47.0
3	75.0	63.0	56.0	50.0
4	85.0	74.0	63.0	56.0
5	88.0	78.5	69.0	58.5
6	96.0	84.0	73.0	65.0
·7	106.5	91.5	79.5	74.0
8	17.0	95.0	86.0	79.0
10	123.5	107.0	93.0	88.0
12	132.5	112.5	96.0	94.0
15	145.0	125.0	111.0	101.0

Table 3 : Breakdown voltage for -190/1900 us Si



ive space charge between the negative charge and the negative electrode. In the vicinity of the electrode the field is grossly enhanced but the ionisation region is drastically reduced. The effect is to terminate ionisation. Once ionisation ceases, the applied field sweeps away the negative and positive space charge from the vicinity of the point and cycle starts again after clearing time for space charge. To overcome this retarding action of the ions a higher voltage is required, and hence negative breakdown voltage is higher than positive breakdown voltage in the gaps with marked non uniform field.

Graph11 : Breakdown Voltage vs Gap Distance For +190/1900 and -190/1900 us Si for r=20



The more important observation is that as the field is becoming more and more non uniform (i. e. gap distance is incresing) the difference between the breakdown strength for positive polarity and negative polarity is also increasing. In case of uniform field positive polarity and negative polarity show the same breakdown strength. The effect is more pronounced in case of non uniform field as the build up of space charge which distorts the field is possible only in non uniform field. The breakdown voltage for 20 mm sphere -sphere configuration for two polarities are shown in graph11. It is clear from this

Gap Distance cm	Breakdown Voltage kV			
	r = 20 mm	r = 15 mm	r = 12.5 mm	r = 7.5 mm
2	60.0	56.5	50.0	45.0
3	73.0	60.5	53.5	48.0
4	82.0	71.0	60.5	53.0
5	84.5	75.5	66.0	55.0
6	92.5	80.0	69.5	61.0
7	102.5	87.5	76.0	70.0
8	113.0	90.5	82.0	75.0
10	119.0	102.5	89.0	83.0
12	127.5	107.0	91.0	89.0
15	139.0	119.0	105.0	94.5

Table 4 : Breakdown voltage for - 250/2500 us Si

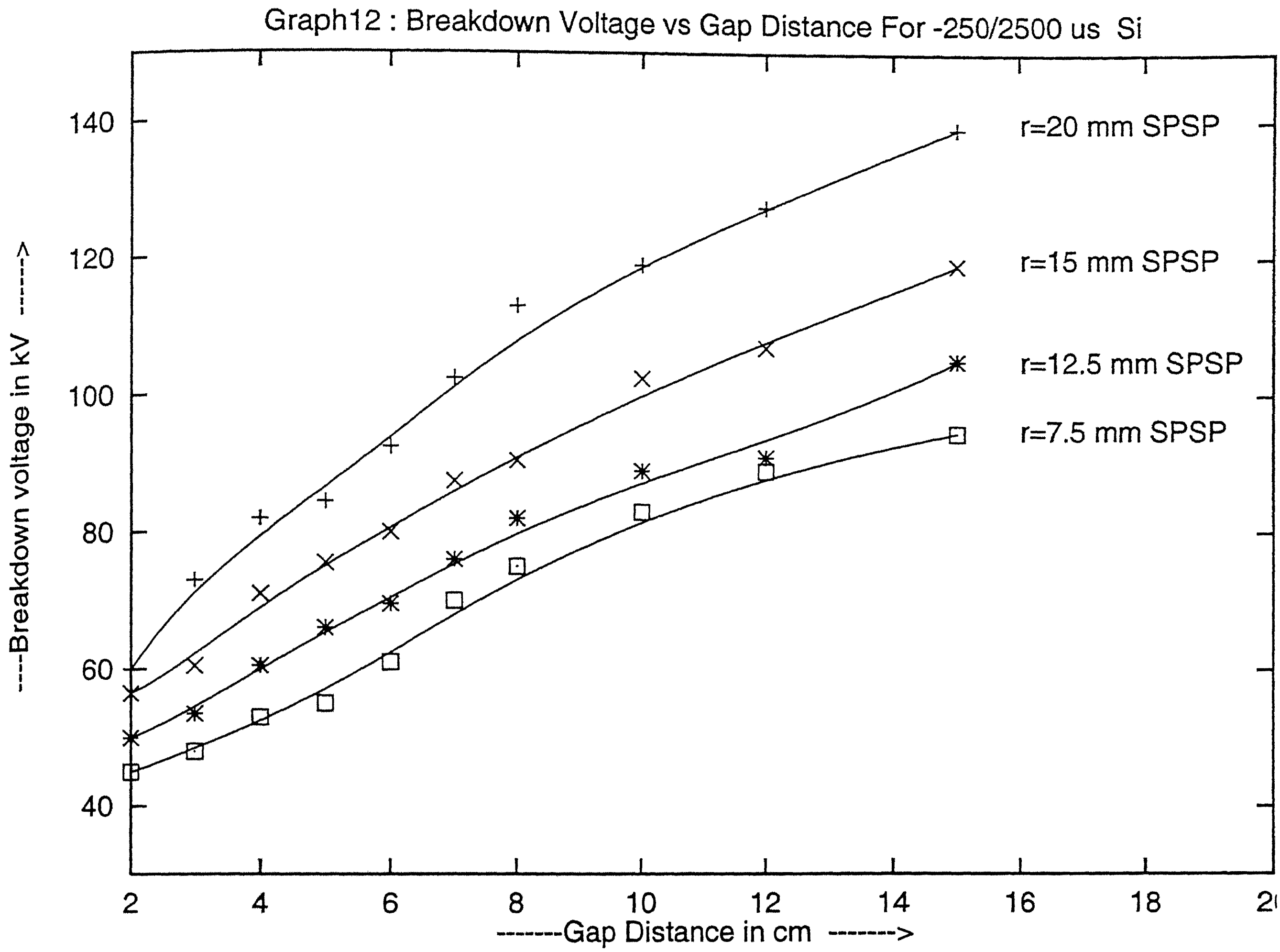
graph that when gap distance is 2 cm the difference between the breakdown voltage for two polarities is 1.5 kV and for gap distance of 15 cm this difference goes up to 15 kV. Data in table3 show the same trend of the graphs for other electrode configurations.

5.2.2 Results With $-250/2500\mu s$ Switching Impulse

Negative switching impulse of $250/2500\mu s$ is obtained by using the internal front resister $R_1' = 20.4\ k\omega$ and discharge resistor $R_2' = 54.4\ k\omega$. The values of breakdown voltage for all sphere -sphere configurations for gap distance varying from 2 cm to 15 cm are shown in table4. Breakdown voltage vs gap distance graphs for all four configurations are plotted on graph 12. The variation of breakdown voltage with gap distance is same as in case of positive polarity, only difference being the

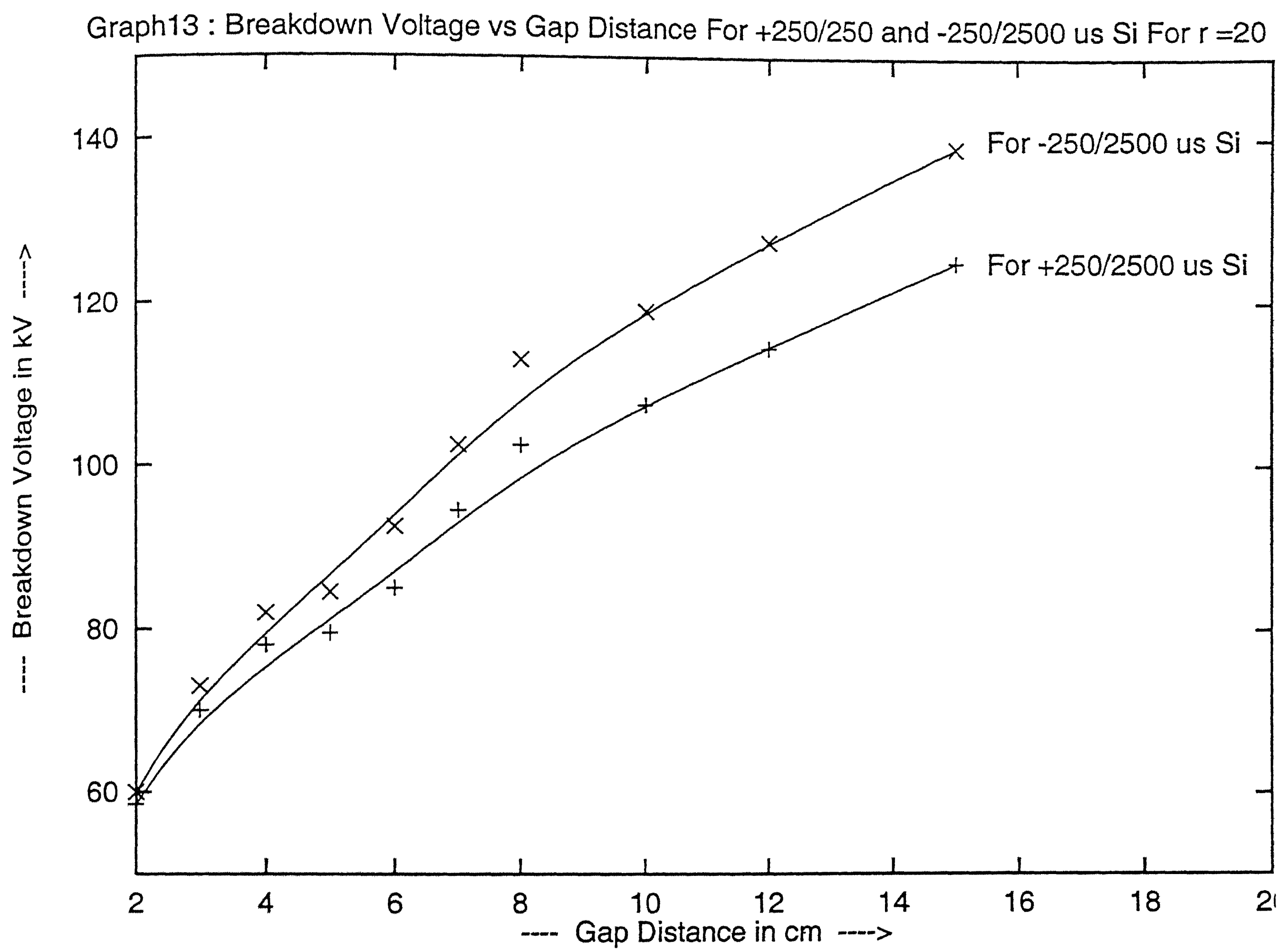
actual values of the breakdown voltage,which are lower in this case.

Breakdown voltage vs gap distance for both negative and positive polarity impulses

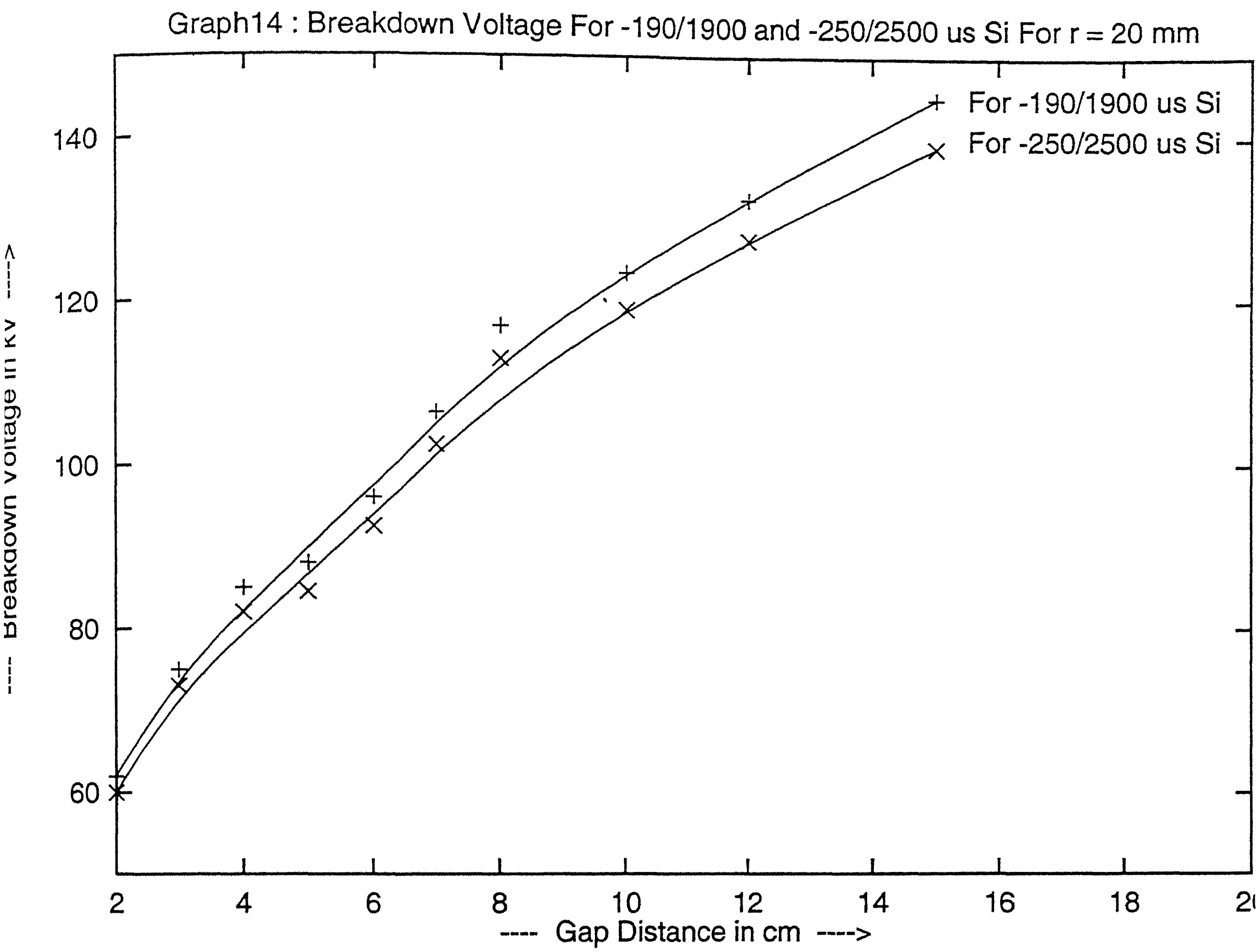


of $250/2500\mu s$ for electrode configuration of 20 mm are plotted in graph13. Breakdown voltages are higher for negative polarity pulse. The difference between breakdown voltage at gap distance of 2 cm is 1.5 kV and it reaches to 14 kV for a gap distance of 15 cm. It is clear that polarity effect is more pronounced when is becoming more non uniform.

When the result of $-190/1900\mu s$ and $-250/2500\mu s$ are compared it is found that the breakdown voltage more for a switching impulse of smaller rise time and tail time. It implies that Si of larger tail time are more dangerous than Si of smaller tail time. The



dielectric should be tested for a Si of lager tail time as it has minimum breakdown strength for this wave shape. breakdown strength against gap distance for these two negative polarities impulse are plotted in graph14 for sphere diameter of 15 mm. Similar graphs can also be plotted for other configurations. Here again one important observation is that the wave shape affects the breakdown strength severely when the field is non uniform. In uniform field the two wave shapes tend to give almost same breakdown strength. In this graphwhen field is weakly non uniform (at d=2 cm) the difference in breakdown strength



for two wave shapes is arround 2 kV while for non uniform field (at gap distance d= 15 mm) this difference increases to 6 kV. If the field is extremely non uniform this difference will further increase. wave shape effect is minimum in uniform field.

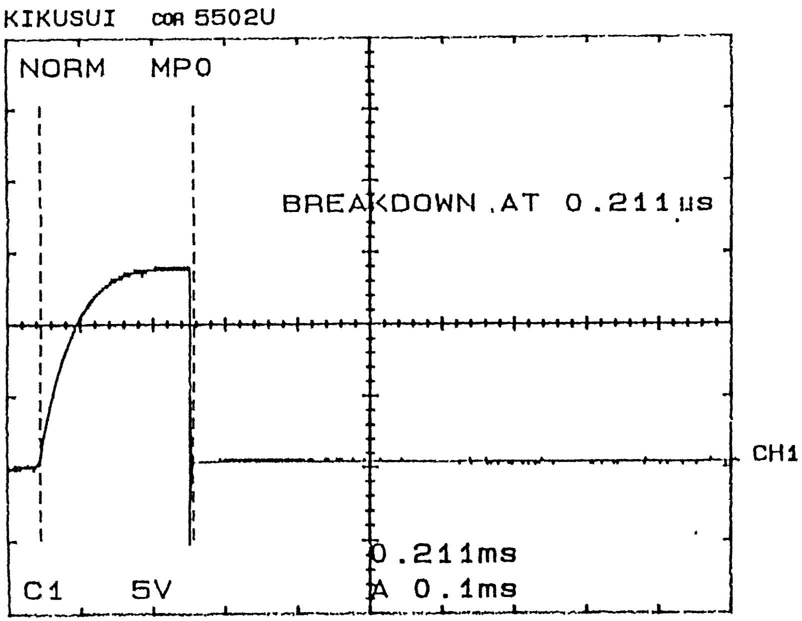
Chapter 6

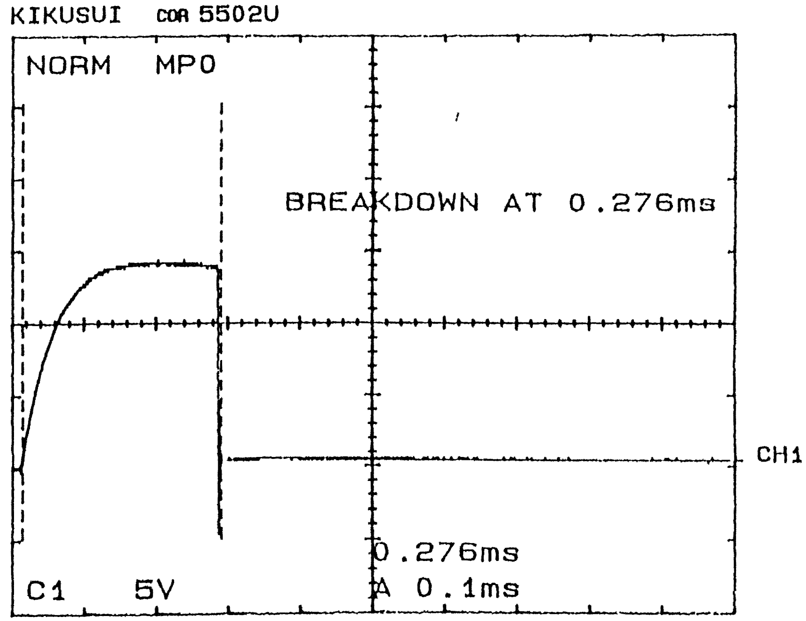
INVESTIGATIONS OF PROPAGATION TIME AND PROPAGATION VELOCITY

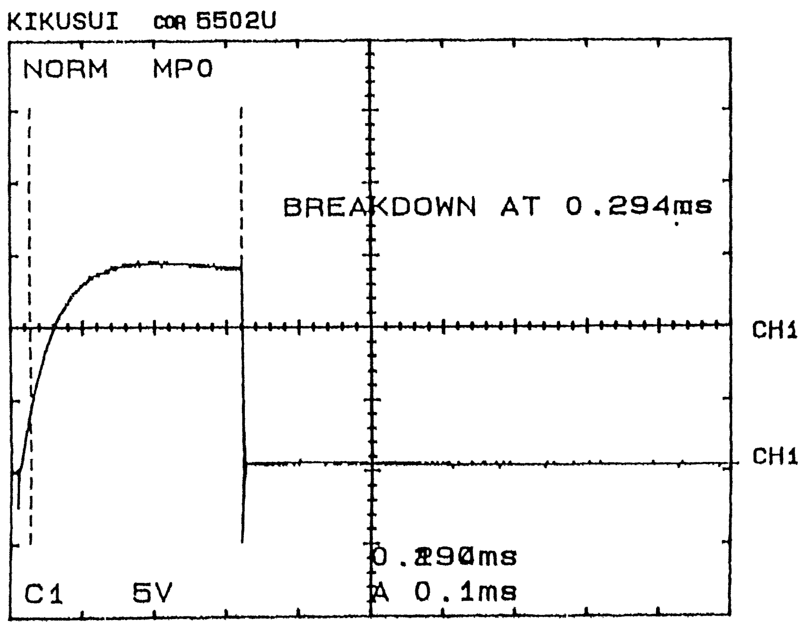
6.1 Investigations With 190/1900μs Si

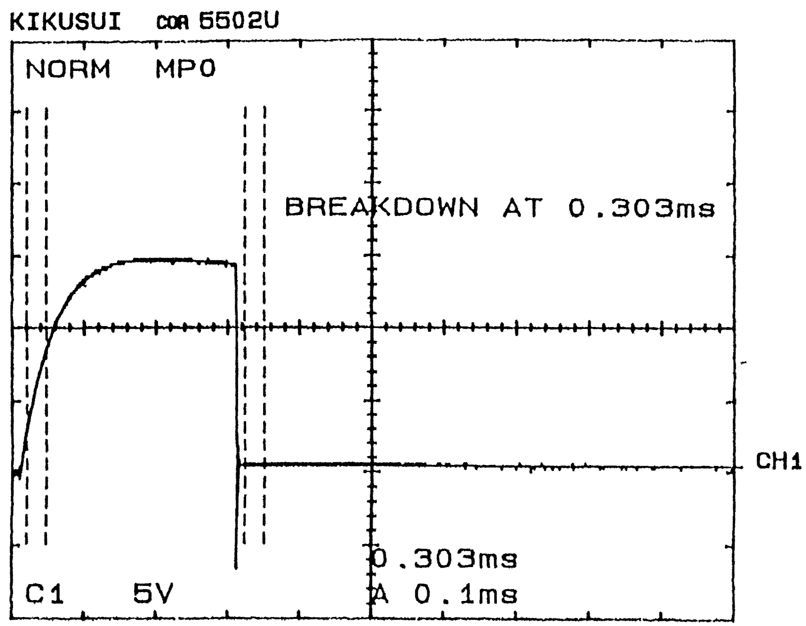
For calculation of propagation time we need to measure time required for leader to pass from one electrode to other. As explained earlier it is measured by mesuring the time required for voltage to come down to zero value from the value at the instant of the begining of the breakdown. The gap distance is varied from 2 to 10 cm in step of 2 cm. For all electrode configurations propagation time is measured. These observations are shown in table5. Propagation velocity is calculated assuming that the leader takes the path equal to the shortest gap distance between electrodes.

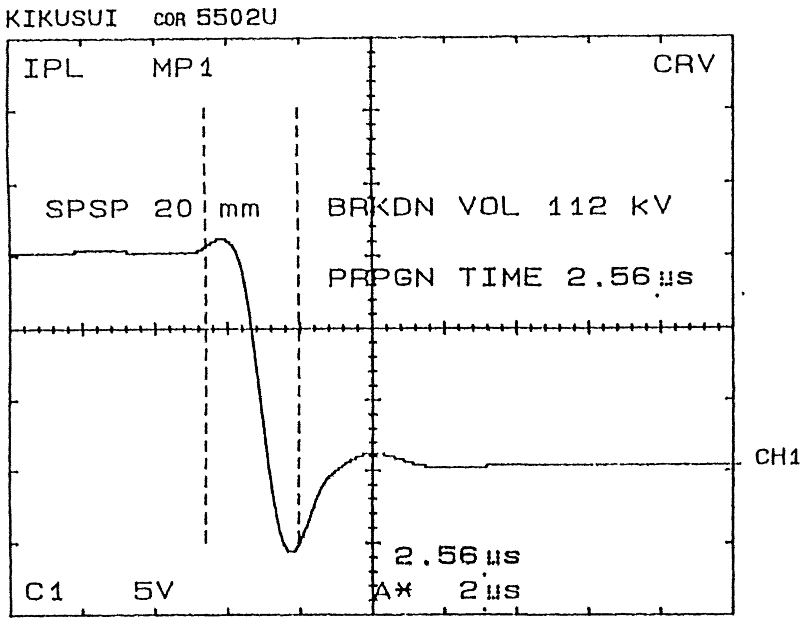
$$Propagation\ Velocity = \frac{GapDistance}{propagationTime} \tag{6.1}$$

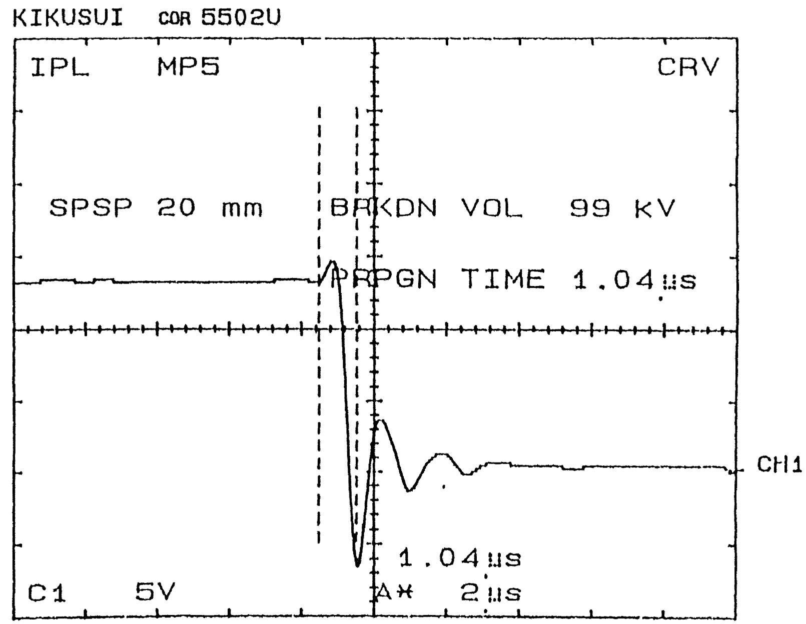

KIKUSUI COR 5502U
NORM MPO
BREAKDOWN AT 0.211 µs
CH1
0.211ms
A 0.1ms
C1 5V

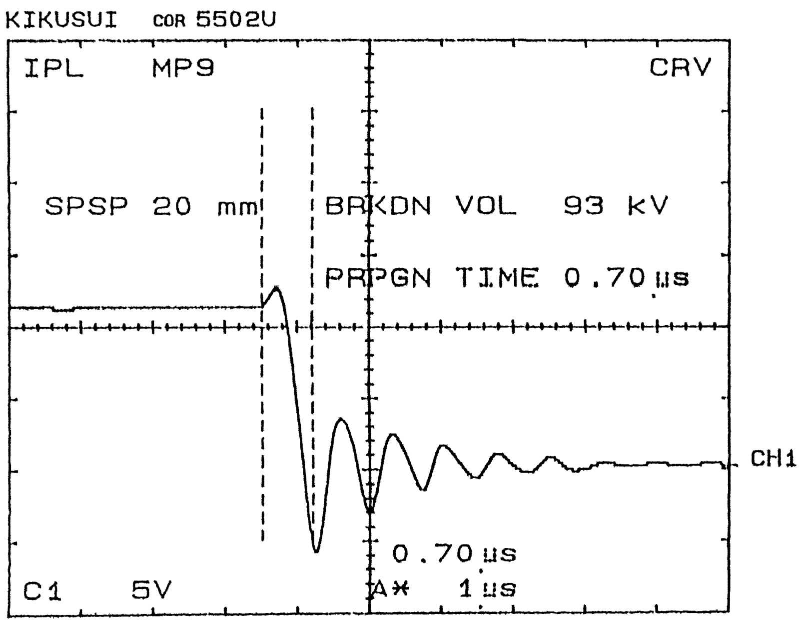

KIKUSUI COR 5502U
NORM MPO
BREAKDOWN AT 0.276ms
CH1
0.276ms
A 0.1ms
C1 5V

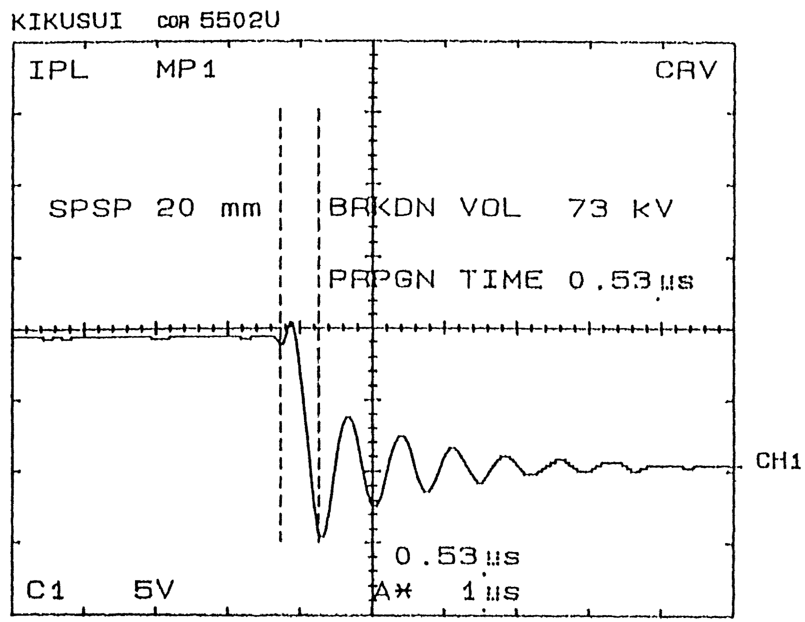

KIKUSUI COR 5502U
NORM MPO
BREAKDOWN AT 0.294ms
CH1
CH1
A 0.1ms
C1 5V

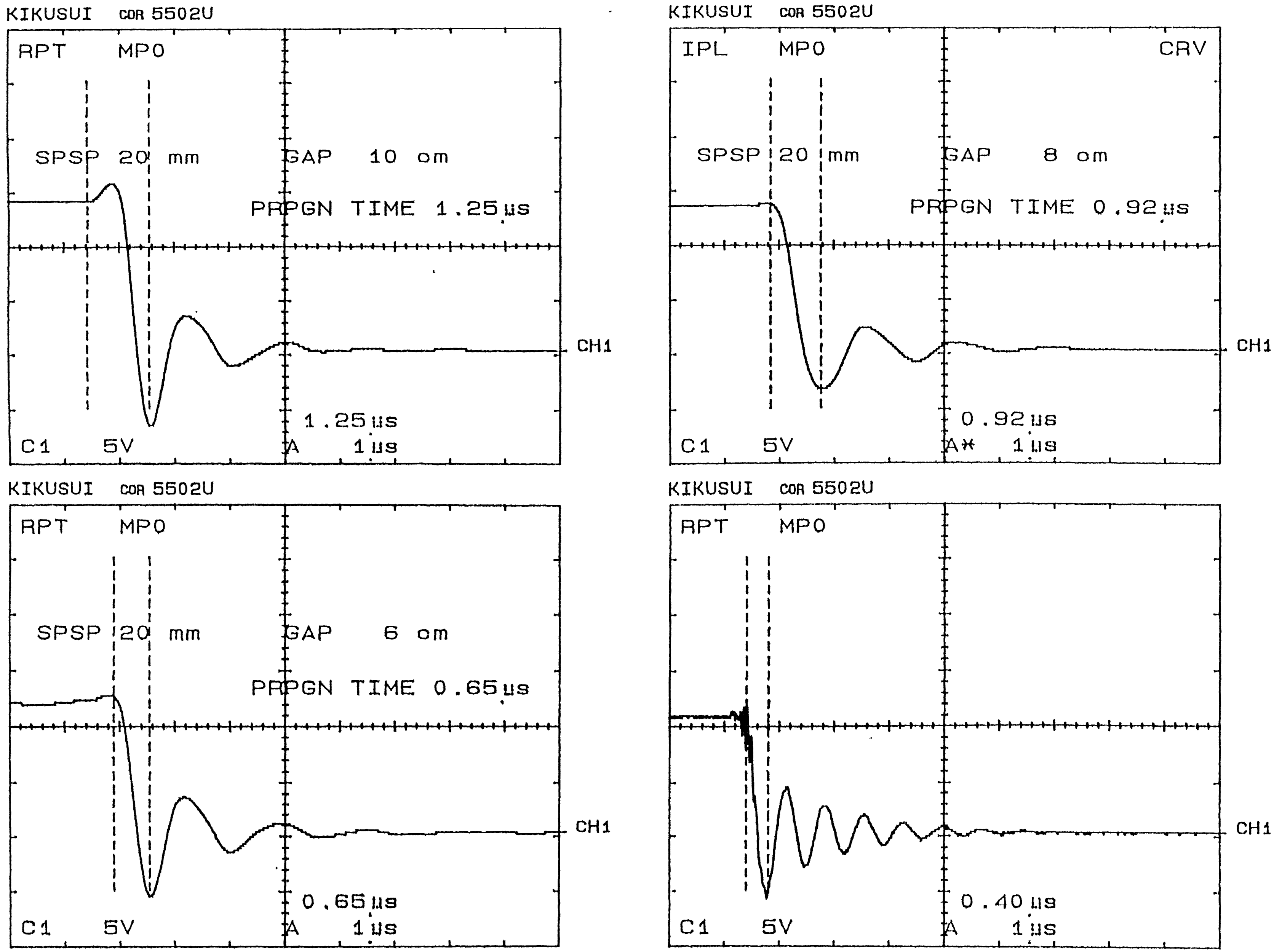

KIKUSUI COR 5502U
NORM MPO
BREAKDOWN AT 0.303ms
CH1
0.303ms
A 0.1ms
C1 5V


KIKUSUI COR 5502U
IPL MP1
CRV
SPSP 20 mm
BRKDN VOL 112 KV
PRPGN TIME 2.56 µs
CH1
2.56 µs
C1 5V
A* 2 µs


KIKUSUI COR 5502U
IPL MP5
CRV
SPSP 20 mm
BRKDN VOL 99 KV
PRPGN TIME 1.04 µs
CH1
1.04 µs
C1 5V
A* 2 µs

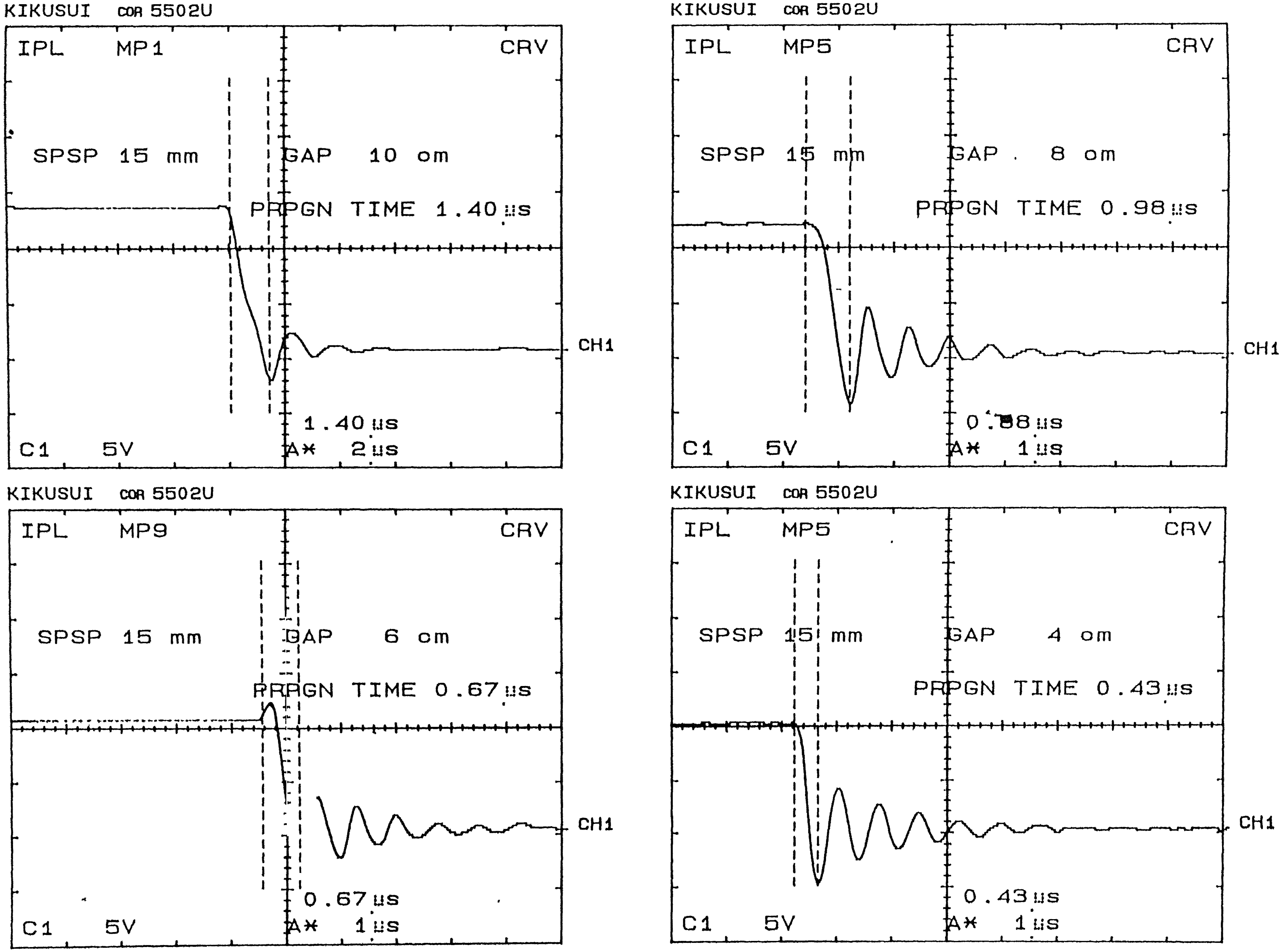

KIKUSUI COR 5502U
IPL MP9
CRV
SPSP 20 mm
BRKDN VOL 93 KV
PRPGN TIME 0.70 µs
CH1
0.70 µs
C1 5V
A* 1 µs


KIKUSUI COR 5502U
IPL MP1
CRV
SPSP 20 mm
BRKDN VOL 73 KV
PRPGN TIME 0.53 µs
CH1
0.53 µs
C1 5V
A* 1 µs

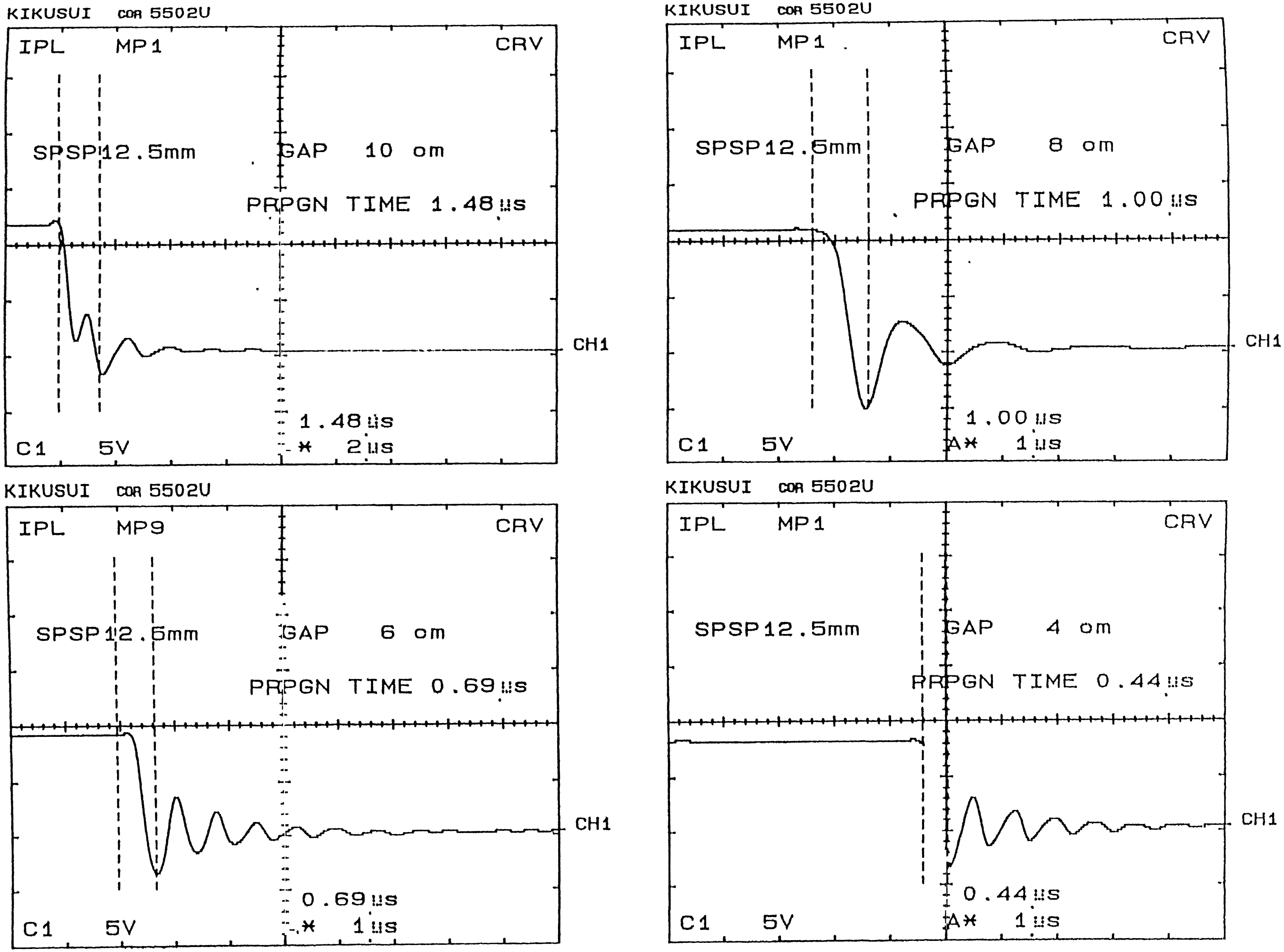


Oscillogram 3 : oscillogram showing variation of propagation time with gap distance for SPSP 20 mm

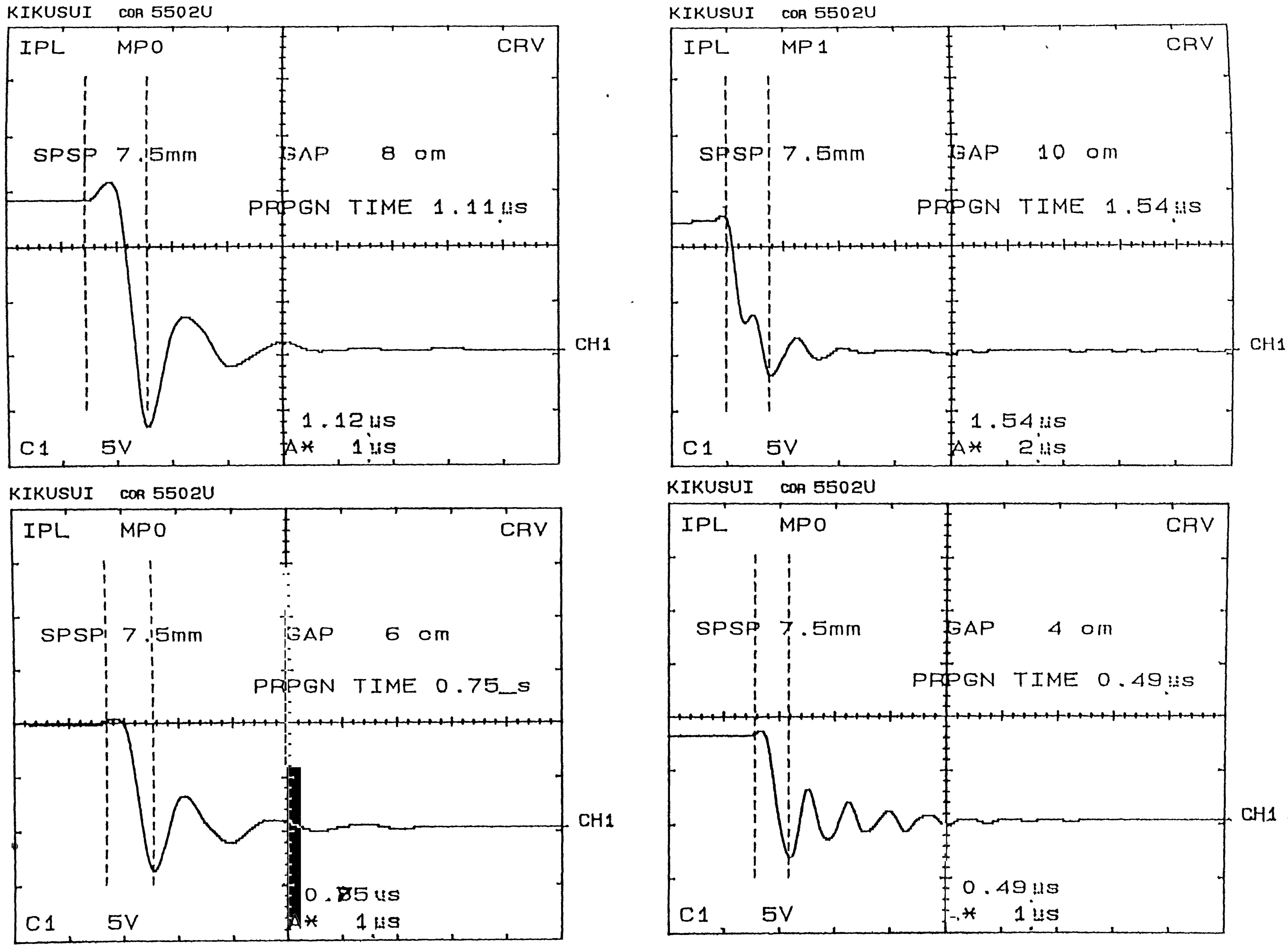
IPL M



Oscillogram 4 : oscillogram showing variation of propagation time with gap distance · for SPSP 15 mm



Oscillogram 5 : oscillogram showing variation of propagation time with gap distance for SPSP 12.5 mm



Oscillogram 6 : oscillogram showing variation of propagation time with gap distance for SPSP 7.5 mm

Gap Distance cm	Propagation time (us)				Propagation velocity cm/us			
	r=20 mm	r=15 mm	r=12.5mm	r=7.5 mm	r=20 mm	r=15mm	r=12.5mm	r=7.5 mm
2	0.17	0.18	0.19	0.20	11.76	11.11	10.52	10.00
4	0.40	0.43	0.44	0.49	10.00	9.23	9.09	8.16
6	0.65	0.67	0.69	0.75	9.23	8.96	8.70	8.00
8	0.92	0.98	1.00	1.11	8.70	8.16	8.00	7.21
10	1.25	1.31	1.48	1.54	8.00	7.63	7.30	6.80

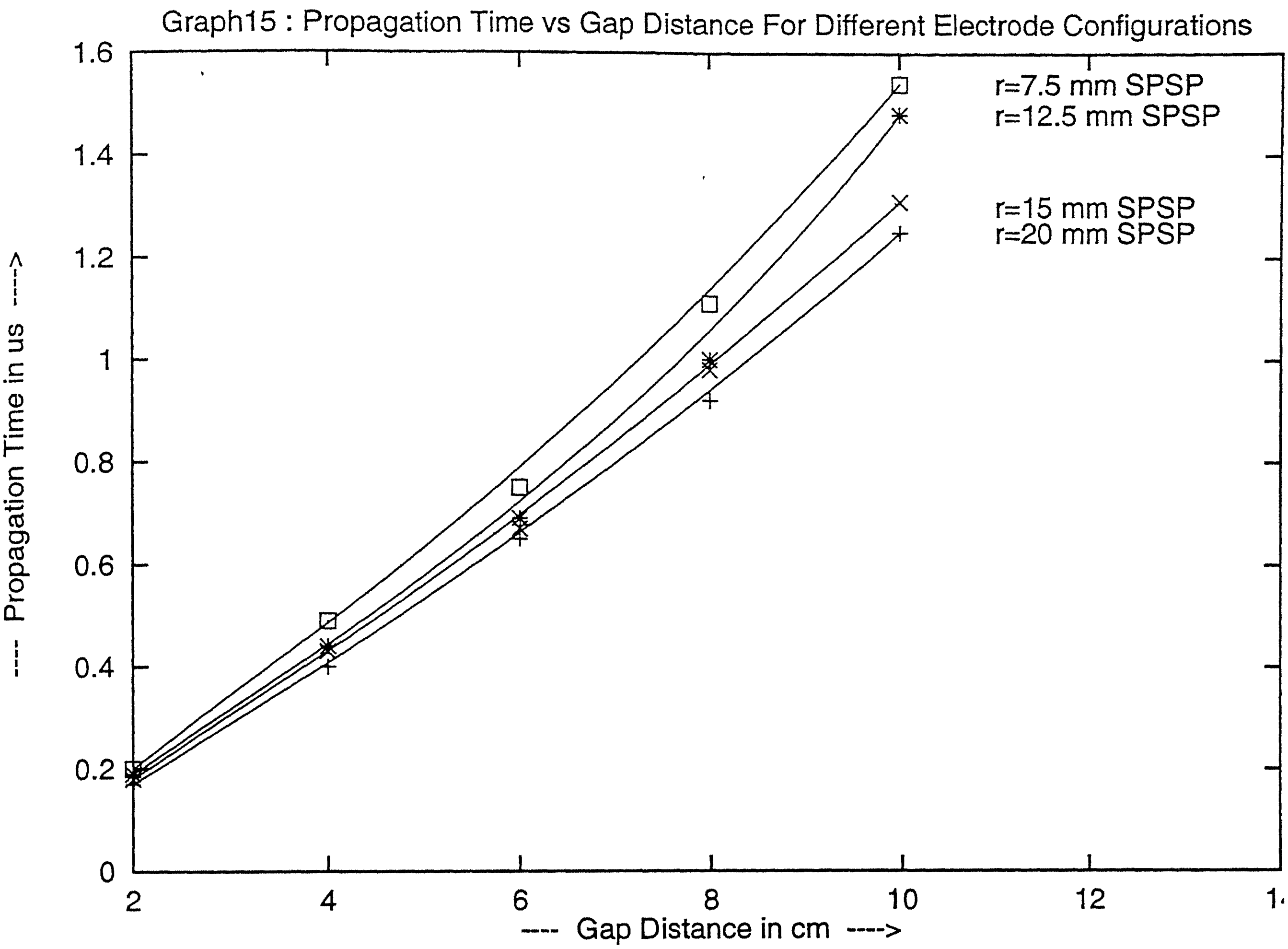
Table 5 : propagation time and velocity for +190/1900 us Si

It was observed that the propagation time depended on the instance at which the breakdown was taking place. It was observed that it was strong function of the time between the peak and the instance at which breakdown took place. If breakdown takes place near the peak then propagation time is more compared to a case when breakdown takes place away from peak. Here an important precaution to be taken is that only those observations have to be recorded for which breakdown takes place approximately at the same time away from the peak. This makes the measurement of propagation time a little difficult as process is to be repeated and propagation time only for those observations for which breakdown takes place at the same (approximately) instant were recorded.

Important observations are as follows:

(A) Variation of propagation time with gap distance :

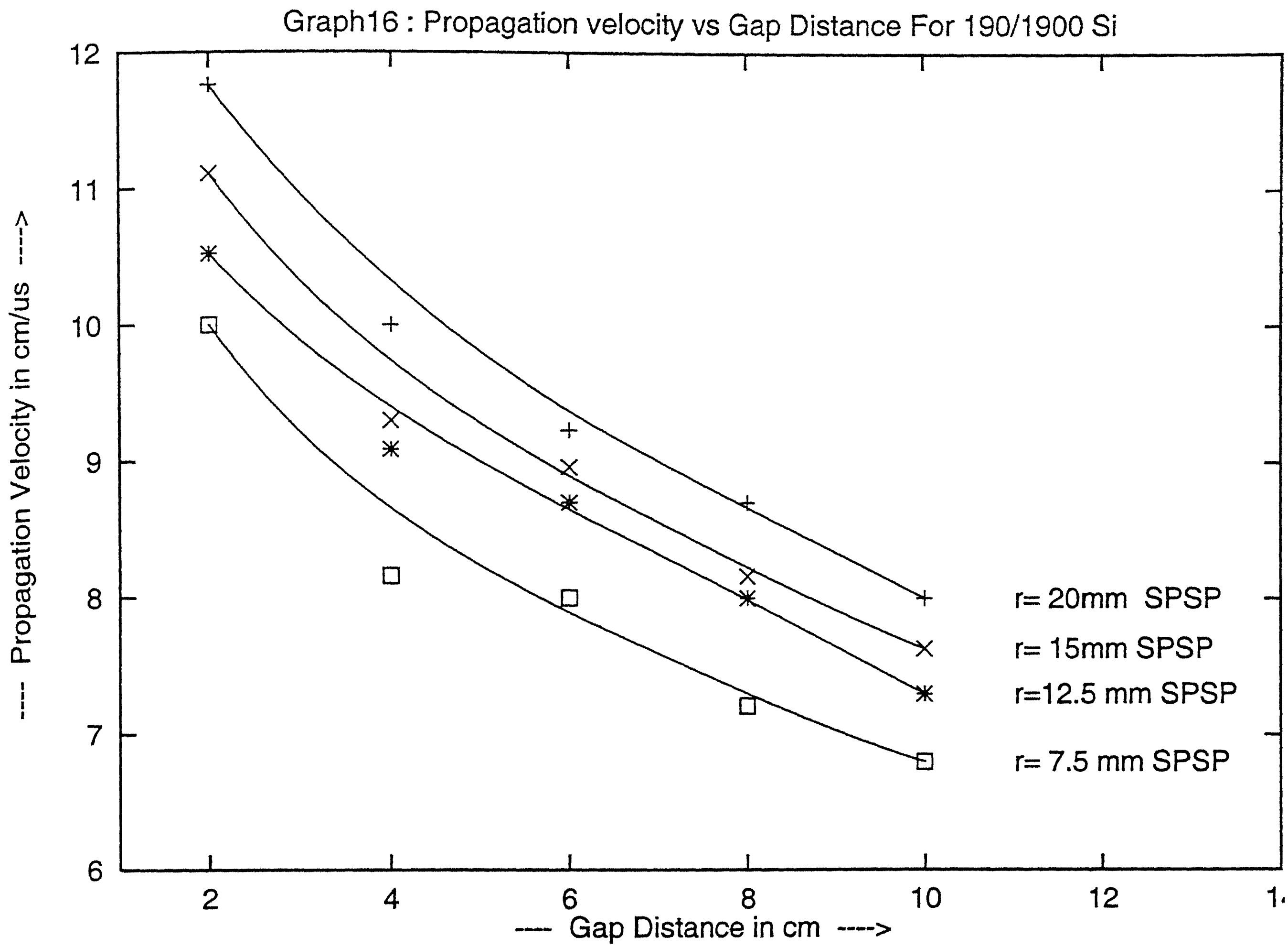
Variation of propagation time with gap distance for all configurations is shown in graph15. It is observed that as gap distance increases the propagation time increases. Propagation time for same gap distance is more for the configuration having smaller



radius of sphere. This implies that propagation time is less in uniform field or to say it is a function of Schwaiger factor.

(B) Variation of propagation velocity with gap distance :

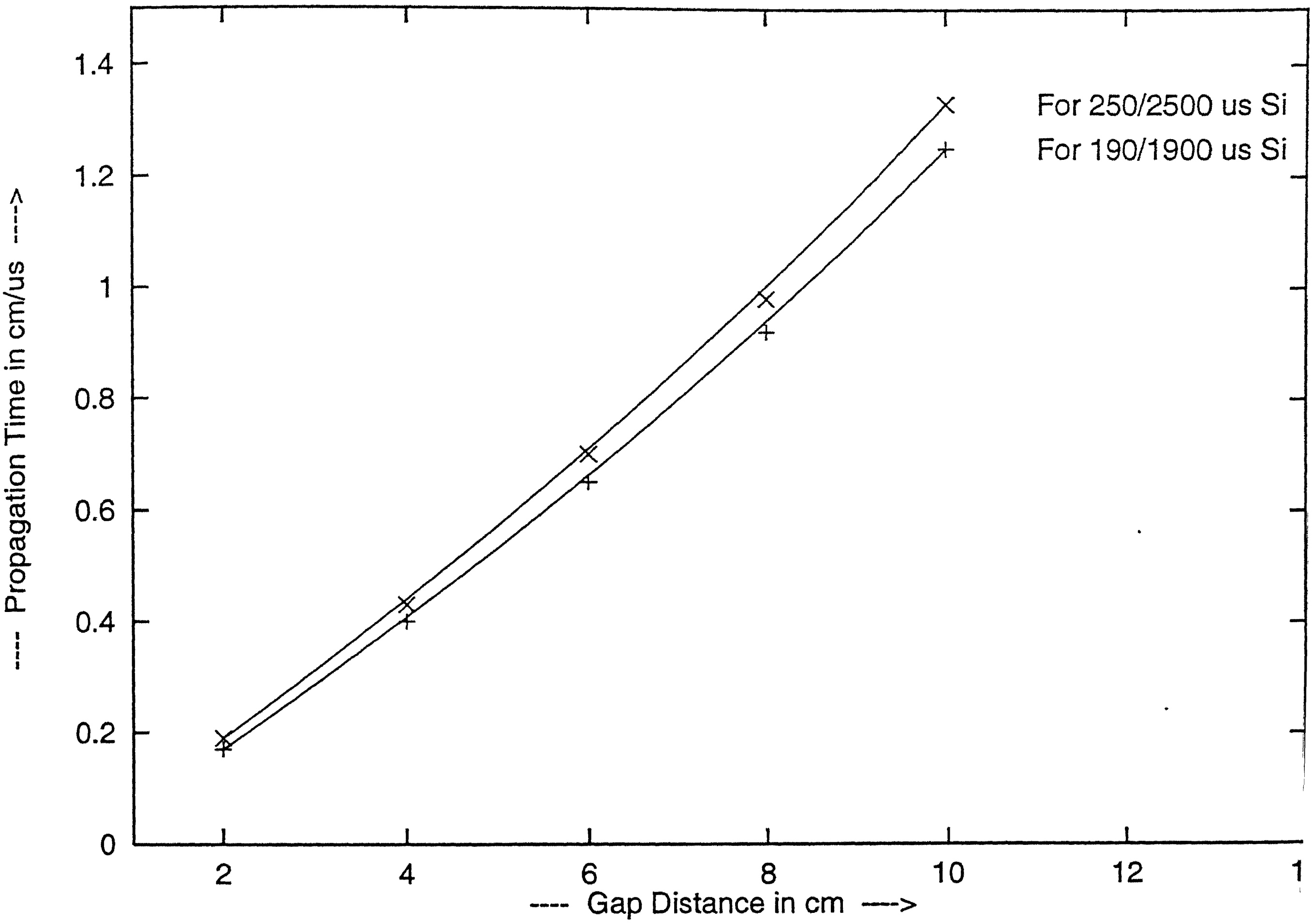
The variation of propagation velocity with gap distance is shown in graph 16 for all elecrode configurations. It is observed that propagation velocity is more when distance between the electrodes is small and becomes less as gap distance is increased. This implies that sa field is becoming more non uniform propagation velocity of leader is decreasing.



For same gap distance propagation velocity is less for the configuration having smaller radius of sphere.

The values of propagation velocities are plotted against Schwaiger factor η. It is observed that for all electrode configurations the graphs are very close to one another ,showing that propagation velocity depends upon the degree of non uniformity. For the same degree of non uniformity the same value of the propagation velosity was measured for all electrode configurations (sphere-sphere).

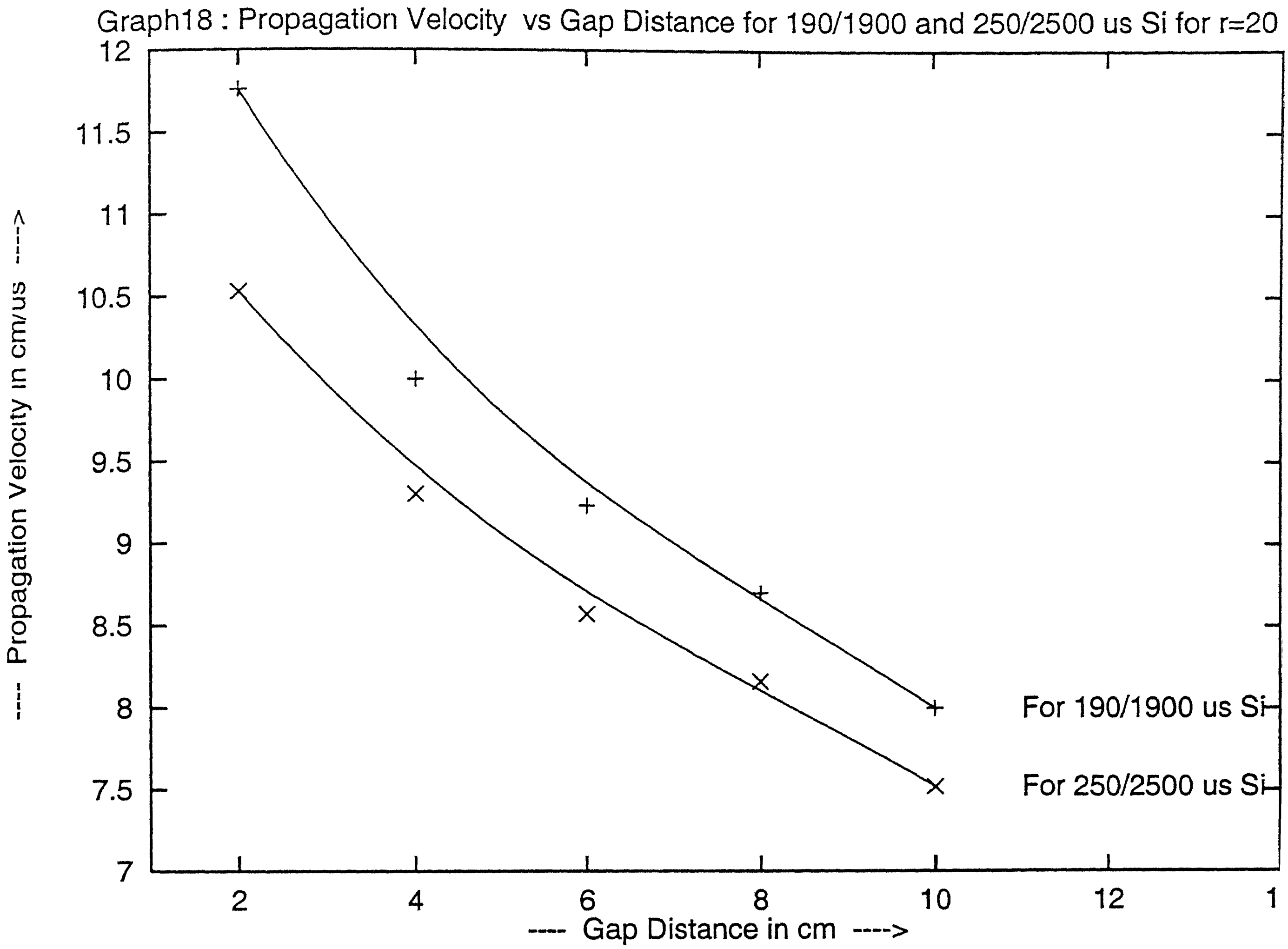
Graph17 : Propagation Time vs Gap Distance for 190/1900 and 250/2500 us Si For r= 20 m



6.2 Investigations With $250/2500\mu s$ Si

Propagation time and propagation velocities for $250/2500\mu s$ Si are recorded in table6. The trend of the variation of propagation time and propagation velocity is same as in case of $190/1900\mu s$ Si. Important observations are obtained when results of propagation time and propagation velocity are compared for the two wave shapes.

The propagation time against gap distance for two wave shapes is plotted in graph17 for r=15 mm sphere sphere configuration. It is observed that propagation time is longer



for 250/2500μs Si. It establishes that propagation time is more for a Si with longer tail time. Infact propagation time is a strong function of the discharge resistor R_2'. It confirmed that higher is the discharge resistor higher is the propagation time as stated by Razevig D. V. in [3].

Variation of propagation velocity with gap distance for two wave shapes for r-20 mm electrode configuration is plotted in graph 18. It is observed that propagation velocity is lower for Si having longer tail time for the same gap distance.

Chapter 7

CONCLUSIONS

Important conclusions of this study are as follows:

(1) For any wave shape breakdown voltage increases as gap distance is increased. The breakdown strength decreases as distance between electrodes is increased i. e. field is becoming more non uniform. The dielectrics has maximum breakdown strength in uniform field.

(2) Breakdown strength of dielectric is maximum for a Si having smaller rise time and tail time.

(3) Difference between breakdown strength for various Si is minimum in case of uniform field. As field becomes more and more non uniform two Si of different rise time and tail time give different breakdown strength.

(4) Breakdown strength of dielectric is larger for negative Si caompared to positive Si of same rise time and tail time.

(5) The polarity effect is maximum in case of non uniform field. In uniform field breakdown strength is same for both polarities.

(6) Propagation time for same gap distance depends upon the instance of breakdown. Propagation time is large if breakdown takes place near the peak. It decreases as the instance of breakdown is shifting away from peak.

(7) For fixed instance of breakdown the propagation time is more when the gap distance between the electrodes is large. It decreases as gap distance decreases.

(8) For a fixed instant of breakdown and same gap distance, the propagation time is less for higher voltage.i.e. for fixed instant of breakdown and gap distance propagation time is less for U_{b-90} compared to U_{b-50}.

(9) Propagation velocity is maximum in uniform field and it decreases as field is becoming more non uniform.

(10) Propagation time is larger for a Si of larger rise time and tail time for same gap distance and same instant of breakdown i. e. propagation time is a strong function of discharge resistor R_2' of IG.

(11) Propagation velocity is smaller for a Si of larger rise time and tail time for same gap distance and same instance of breakdown.

(12) Propagation time and ropagation velocity depends on the degree of non uniformity. For same degree of non uniformity all electrode configurations give same propagation

velocity and propagation time.

Scope of further Research :

(1) Due to limitations of experimental set up gap distance cuold be changed only from 2 cm to 15 cm. By properly designing the experimental set up behaviour of dielectric could be analysed for extremely non uniform field.

(2) A more accurate analysis could be done uy using spheres of larger radius and using smaller currents by using a current limiting resistor.

(3) Similar observations could be made for li of different rise time and tail time as dielectrics in power systems are more exposed to li.

(4) Breakdown strength could be analysed in uniform field and extremely non uniform field using Rowgough profile electrodes and point plane electrodes respectively.

(5) If in future it is possible to breakdown the dielectric at a required instance then accurate variation of propagation time with voltage and gap distance can be analysed. In this study only those observations are taken for which instance of breakdown is approximately equal,as it is not possible to breakdown the dielectric at required instance by using present experimental set up.

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